

**UNIVERSITY OF VAASA**

**FACULTY OF BUSINESS STUDIES**

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**LINKAGES OF MAJOR CARRY TRADE CURRENCIES:  
A WAVELET ANALYSIS**

Master's Thesis in  
Accounting and Finance

Finance

VAASA 2013

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| <b>Year of Entering the University:</b> | 2011  |                  |
| <b>Year of Completing the Thesis:</b>   | 2013  | <b>Pages: 89</b> |

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**ABSTRACT**

The aim study provides the new perspective for currency portfolio management by studying the linkages of major eight currencies with an implication to the currency arbitrage strategies. The financial data for the sample of 5895 daily observations for each of eight chosen currency as well as LIBOR rates was gathered and examined for the period over the past 22 years. Wavelet analysis techniques are used to study the temporal structure of correlations, cross-correlation of volatilities and coherence spectrums of eight major carry trade currencies with U.S. dollar as base currency. Wavelet correlation analysis showed that in the group of investment currencies with high interest differential upward trend in term structure of correlations is observed. Therefore, the benefits of diversification among investment carry trade currencies are much higher at short investment horizons. Additionally, strategy built on the basis of wavelet correlations of returns and diversification efficiency ranking has led to Sharpe ratio 30% higher than the simply diversified portfolio. Further, results of wavelet cross-correlation analysis of volatility series allow investors actively involved in currency trading, in some sense, predict changes of volatility and, therefore, minimize risk. The Japanese yen volatility is leading the volatility of Australian dollar, New Zealand dollar. Perhaps, such clear lead-lag relations of Japanese yen and carry trade investment currencies are caused by the nature of currency arbitrage. Finally, results of wavelet coherence analysis indicate relatively high dependences of exchange rates at low frequencies (one year and above), while at high frequencies high degree of co-movement is observed mainly during financial crises and high volatility on the market, indicating contagion. Financial crisis of 2008 appeared to have strongest impact in terms of increased short term correlations at high frequencies, those effects can be observed today. Wavelet coherence maps also indicate an overall increase of correlation in most of the cases during the last 22 years, reflecting the facts of integration of world economies, increasing trading volume on foreign exchange market and globalization in general.

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**KEYWORDS:** FOREX, Carry Trade, Wavelet





## 1. INTRODUCTION

The last decade is associated with increasing internationalization processes (in terms of reducing differences between national economies) and globalization (in terms of territorial availability of capital). Together with the increasing volume of investment in the development of information technology, these processes lead to an increase in the availability of foreign currency and financial markets for investors. The foreign exchange market (FOREX) is the single biggest financial market in the world. With the daily trading volume about four trillion US dollars (BIS Survey 2010) FOREX is more than 12 times bigger than all global equity markets (about 320 billion of U.S. dollars a day according to the World Federation of Exchanges, 2009). An annual foreign exchange market turnover more than 15 times world GDP - about 58 trillion U.S. dollars (World Bank 2009). It has a very large number of daily participants, which makes its liquidity one of the highest in the world. The foreign exchange market is important because it provides participants with four major functions, namely, currency conversion, currency hedging, currency arbitrage, and currency speculation. If any market is efficient it should be the FOREX market. Prices should fully reflect information available to market participants. Hence, it has to be impossible to derive excess returns from speculation as no arbitrage opportunities arise. However, there is evidence of systematic ability to earn excess returns in FOREX markets.

There is an extensive literature on the EMH for foreign exchange markets. Empirical studies constantly reject the FOREX efficiency hypothesis and show that neither uncovered interest rate parity (UIP) nor covered interest parity (CIP) do not hold in the real world. UIP is a no-arbitrage condition which implies that high interest rate currencies should depreciate low interest rate currencies, so under such equilibrium investors would be indifferent to the interest rate in two countries. On the contrary with the theory, Bilson (1981) and Fama (1984) empirically show the failure of UIP. This violation of UIP is often referred as forward premium (forward bias) puzzle. Burnside, Eichenbaum, Kleshchelski and Rebelo (2006) show that the Sharpe ratio generated by carry trade strategies is positive and statistically different from zero. Moreover, on average high interest rate currency tend to appreciate, so arbitrage opportunities arise. Despite

the existence of carry trade excess returns over uncovered interest parity currency arbitrage is often viewed by professionals as “picking up penny in front of the track”. Recent studies posted the results proving the results that this statement is not inevitable and single arbitrageur can tailor the portfolio with needed characteristics. It was proved that simple diversification across currencies lead to significant increase in Sharpe ratio. Such studies as well as scientific back ground of carry trade returns are covered in the following sections.

However, existing literature just scratched the surface of portfolio composition and could, however, be misleading due to the temporal instability of correlation coefficients used. Hence, further analysis of diversification opportunities using more advance methodologies is essential. Previous researches mainly were focused on temporal correlation and sometimes its time variations. The contribution of this study is the addition of new dimension for the analysis of most common carry trade currencies correlations. This research utilizes wavelet analysis, which focuses on the changes in scale – dimension, instead of time changes framework.

### 1.1. The Purpose of study and Contribution

Current study traces the nature of systematic excess returns in FOREX market, by analyzing, compering and complementing the findings on currency linkage and interdependence. The aim study provides the new perspective for currency portfolio management by studying the linkages of major eight currencies with an implication to the currency arbitrage strategies. Study develops the tools for efficient diversification is essential for portfolio management as well as risk management, simultaneously taking in to account the scientific nature of excess returns. Further, study provides broad perspective of foreign exchange market properties with an implication to currency arbitrage in the past 22 year, building the coherence maps for analyzed currencies.

While there exists an extensive literature mainly investigating integration of stock markets and approaching international portfolio diversification issues, linkages of the currencies has mostly been neglected. Study differs and, to some extent, contributes previous papers in two respects:

- (1) Although the Wavelet Analysis of financial time series and Maximum Overlap Discrete Transform (MODWT) techniques have been used extensively to study the co-movements of major stock market indices, but these techniques have not been used to study the interrelations of currencies in a thorough way. In this study, the Wavelet analysis techniques are used to study the temporal structure of correlations, cross-correlation of volatilities and coherence spectrums of eight major carry trade currencies with U.S. dollar as base currency.
- (2) Dataset utilized in current study allows capturing the patterns in co-movement behavior of currencies during past 22 years major recent financial turmoil. This study is tracing the relations of four commonly identified funding and investment carry trade currencies.

## 1.2. Hypotheses

The following three hypotheses based on the ground of theoretical framework and previous empirical results of prior studies are identified. Following previous findings, it is possible to formulate the main hypotheses of this paper that are going to be tested. Therefore, the arguments are that:

The first alternative hypothesis is based on an objective understanding that a simple equilibrium diversification leads to a significant increase of investment attractiveness of the carry trade. Burnside et al. (2011) show that in carry trade strategy diversification among 20 major currencies doubles Sharpe ratio. Diversifying across currencies causes cut volatility. Studies by Ranta (2010), Nekhili et al. (2002), Gensay et al. (2002) indi-

cate the importance of scale-based analysis. Consequently, the study of wavelet correlations of exchange rates may reveal the fact of integration and interdependence of currencies. This conclusion will help to better understand the structural characteristics of the relationship of exchange rates. This study has significant practical value in the investment strategies and risk management. Term structure of exchange rate correlations and trends in correlations is crucial from the practical point of view, as correlation is the key factor to efficient portfolio diversification, and scientific perspective, such analysis may show that interrelations between currencies exist and profitable arbitrage is possible.

H1: Patterns in the term structure of exchange rate correlations and interdependence of rates exist, trends in the correlation of exchange rates with implication to carry trade portfolio diversification can be found.

The second alternative hypothesis is based on the assumption of volatility lead-lag relationship of different exchange rates. Previous studies show the presence of such links on the various stock markets (e.g. Knif et al. 1995; Ranta 2010; Krylova et al. 2009; Nikkinen et al. 2006). Volatility tends to propagate (often used term "overflow") across borders of different countries causing a chain reaction and increase the fluctuations in asset prices. It can be argued that if these relationships are found, such information may have a significant practical value for investors (currency arbitrageurs). The hypothesis is drawn from the nature of currency arbitrage. Changes in volatility of funding (investment) currency may lead to rapid unwinding or building up the carry trade position, consequently, causing the change of investment (funding) currency volatility.

H2: Lead-lag relationship in the volatility of various carry trade currencies exist.

The third hypothesis is based on the concept of "contagion." This concept is based on the basic interdependencies in the global financial system. In times of crisis, the interdependence and correlation between economies and financial markets increases, reducing the benefits of diversification and allocation, between assets and between different economies. Prior studies document the strong contagion effect of major stock markets

on the high frequencies during turmoil. (e.g. Graham et. al 2012; Graham et. al 2011; Forbes et. al 2002). Similar results may be found in his study by analyzing the data of the foreign exchange market.

H3: Short time scale correlation between exchange rates increases during the market turmoil, simultaneously long time scale correlations remain at the same level, indicating contagion.

Chapter 6 provides empirical test of these hypothesis and supplies additional results obtained from the analysis.

### 1.3. Structure of the Thesis

This study is constructed as follows: first theoretical framework is provided in second third and fourth chapters with the coverage of base theories, concepts and relevant previous literature review; further data and methodological background are described, followed by empirical section of the paper and concluding remarks.

First four chapters are aimed to introduce research topic providing theoretical background. Second chapter stands for brief introduction of market efficiency concept, spot-forward rate linkage on foreign exchange market and coverage of main empirical studies on covered interest rate parity. The evidences on uncovered interest rate parity failure from the previous empirical researches are depicted in chapter three, followed by carry trade strategy definition. The following chapter reviews previous findings and concepts of carry trade excess returns. Data and methodology are described in chapter five in more details, while appendix provide the reader with programming codes written for research conducting with purpose of replicability of the research. Chapter six is presenting empirical results obtained from conducted tests and observations. Chapter seven concludes the paper suggesting some ideas for further research on discussed issue.

## 2. MARKET EFFICIENCY AND ARBITRAGE

According to Efficient Market Hypothesis prices reflect all available information on the market. Since information flow is random prices follow random walk. The efficiency or inefficiency of a FOREX market has policy implications of considerable importance (Pilbeam 1992). If a FOREX market is inefficient, it is possible to develop a model that predicts exchange rate fluctuations. Hence, some patterns in exchange rate movements can be found. Therefore, it has to be possible to consistently derive riskless excess returns from speculation as arbitrage opportunities arise. Further, in an inefficient foreign exchange market, the regulation authorities can determine the best way to influence exchange rates and evaluate the consequences of different economic policies. Alternatively, a foreign exchange market that is efficient needs minimal intervention and its participants cannot obtain excess returns from foreign exchange speculations. Further, in efficient markets participants cannot receive abnormal returns, since no arbitrage opportunities exist.

It follows that in an efficient market (equilibrium) international investors will have no desire to switch investments from domestic to foreign currency denominated assets, or vice-versa:

$$(1) \quad E_t (\Delta S/S)_{t,t+T} = (i_{t,T} - i_{t,T}^*)$$

Under this equilibrium expected capital gain/loss in one country exactly offset by differential in nominal rates of return, so under such equilibrium FOREX market participants would be indifferent to the interest rate in two countries. EMH can be reduced to the joint hypothesis that:

- FOREX market participants are risk neutral
- FOREX participants have rational expectations

Risk neutrality of market participants means that among two investment opportunities investor will choose one which provide highest return regardless of risk embedded in it. In an aggregate sense, participants act as if they are endowed with rational expectation (Pilbeam 1992).

## 2.1. Spot- Forward rate FOREX market link

Forward foreign exchange market facilitates the purchase or sale of FOREX at an agreed contracted price (in terms of domestic currency) at some specified date in the future. This exchange rate is known as the forward rate. The forward exchange rate is set by a parity relationship among the spot exchange rate and differences in interest rates between two countries, which reflects foreign exchange market equilibrium under which arbitrage opportunities do not exist. When equilibrium holds, parity conditions implies that forward rate comprises forward premium or discount reflecting interest rate differentials between two counties. Forward rate has considerable economic implication in the sense of determining spot rate at the time  $t$  in the future.

Most often, FOREX market efficiency discussions have taken place in the context of the link between spot and forward FOREX exchange rates. When both covered and uncovered interest rate parity hold, they expose a relationship suggesting that the forward rate is an unbiased predictor of the expected future spot rate (Copeland 1994). Forward rate also reflects market expectations (adjusted for risk and formed rationally) of the level of the future spot exchange rate which will prevail at the time the forward contract matures:

$$(2) \quad E_t (S_{t+T}) | \Omega_t = F_{t,T}$$

These expectations are formulated rationally given set of information  $\Omega_t$  at time  $t$ . Hence, at time  $t$  market participant can buy/sell foreign currency at future spot rate



without making side-payment for undertaking risk. As such forward rate  $F_t$  perceived by the market at time  $t$  as an accurate predictor of future spot rate (at time  $T$ ).

## 2.2. Covered Interest Parity

Further,  $F_t$  reflects the appropriate (time  $t$  to  $T$ ) interest rate differential between the domestic and foreign currencies. Interest differentials are those between the domestic currency and relevant foreign currency. Covered interest parity states that the domestic rate must be higher (lower) than the foreign interest rate by an amount equal to the forward discount (premium) on the domestic currency (Copeland 1994).

$$(3) \quad \left(\frac{1}{S_t}\right) \left(1 + i^* \left(\frac{T}{360}\right)\right) F_{t,T} = 1 + i \left(\frac{T}{360}\right)$$

Under this parity arbitrageur is involved in so-called forward market repo speculation. Thus, the investor receives domestic currency at time  $T$  in the amount of  $(1/S_t)(1 + i^*(T/360))F_{t,T}$  and subsequently uses the proceeds to repay the domestic currency loan taken, which exactly the amount of  $(1 + i(T/360))$ . As the result of engaging in this speculation increased borrowing in domestic currency increases the demand for domestic loans. Subsequently, increased sales (purchases) of domestic (foreign) currency in the spot market create excess supply (demand) and reduces (increases) the value of domestic currency (foreign). Same happens in the forward market. Consequently, increased demand for foreign currency investments creates an excess supply of foreign currency deposits, so banks reduce their interest rates for foreign currency deposits. This process continues until the equality is restored. This equilibrium is called covered interest parity.

Forward premium (discount) is the profit (or loss) per unit of domestic currency that a domestic investor will make on his foreign exchange transactions. In equilibrium, when the investor is indifferent between investing in domestic or FOREX it follows that the total “covered” return on the FOREX investment, the latter being equal to the inves-

tor's interest earnings on the FOREX investment plus the foreign exchange transactions profit (or loss) on the round trip transaction.

$$(4) \quad CID = i_{t,T} - i_{t,T}^* - FP_t$$

Thus, in equilibrium covered interest differentials (CID) equal zero. If  $CID > 0$ , then the covered interest differential favors investment in domestic currency. There will be a flow of financial capital into domestic currency assets to earn a risk-free return and vice versa if CID lower than 0. However, non-zero CIDs can occur within the neutral band but they are consistent with the CIP condition, and no profitable arbitrage opportunities after it has been adjusted for such transaction costs (Copeland 1994).

### 2.3. Empirical Evidence and Covered Interest Parity test

Absent buy-sell spreads, CIP states that the Covered Interest Differential (CID) between two identical assets denominated in different currencies should be zero. Assets should not differ in terms of default or political risk refers to the possibility of government's introducing capital controls that reduce the ability of investors to repatriate their funds. If  $CID \neq 0$ , then this may imply a riskless arbitrage opportunity is available. This would suggest the market is inefficient.

The vast literature is dedicated to empirical test of CIP. There do now exist a number of studies which have reported deviations from covered interest parity, for a variety of assets and currencies. Tests conducted on market data, which necessitates the need to control for buy-sell spreads may imply statistical significance differs from economic significance. Majority of studies show that CIP holds on average, accounting for buy-sell spreads.

Threshold regression based study by Peel and Taylor (2002) test the Keynes (1923)/Einzig (1933) conjecture concerning covered interest rate arbitrage in the inter-

war, pre-gold standard foreign exchange market. The essence of this conjecture is, first, that CIP deviations not arbitrated unless this yielded substantial 50 basis points profit (annual basis), second, that deviations from CIP even outside of this range may be arbitrated away only slowly either because of banks' prudential limits on foreign balances or because of market inefficiencies. By analyzing USD/GBP rates during 1920's they supported conjecture and proved the existence of CIP deviations. Hence, in covered period there was CIP deviation, so arbitrage opportunities existed. However risk-free profit could not be exploit due to limits to arbitrage, such as: (i) liquidity issues i.e. banks could not place large "bets" which would significantly reduce overall bank liquidity, (ii) fear of bank runs, (iii) technological restrictions in 1920s of being able to undertake simultaneous transaction. Although, there is considerable statistical significance of CIP deviations economically they are insignificant, accounting for arbitrage limitations. Empirical evidence supports CIP. However, alpha is not zero, but it may be explained by transaction costs. Since beta equals one the conclusion is that CIP holds on average, accounting for buy-sell spreads and other limits to speculation.

Beside regression based estimations of CIP, it is tested based on deviation of covered interest rate differentials (CID) from zero. Classic contribution for this group of studies was made by Frenkel and Levich (1975; 1977). Using Eurocurrency and U.S. treasury (3 month) rate for the GBP/USD and CAD/USD covered interest differentials were estimated. They found a large number of non-zero CIDs, which proves the statistical failure of CIP. However, transaction costs create a neutral band within which interest differentials and the forward premium/discount can fluctuate, so there are no unexploited economic profit opportunities. Frenkel and Levich found 80% of non-zero CIDs for Treasuries and approximately 100% for Eurocurrency rates are in neutral band zone. In conjunction with results authors conclude that "the empirical data are consistent with the interest parity theory in the sense that covered interest arbitrage does not seem to entail unexploited opportunities for profit." (Frenkel et al. 1975: 337)

Consistent with previous study results were found by Taylor (1987). Through analyzing uses high-quality, high-frequency contemporaneously sampled data USD/DEM/GBP Euro-market data study discovers very few profitable violations of CIP. The results of

analyzing these data fully support the market efficiency hypothesis by confirming the covered interest rate parity condition. Further, paper by Taylor (1989) studies the same set of high-frequency, high-quality data sampled around a number of events known to have introduced news or turbulence into the FOREX markets. Taylor finds that there are no exploitable profitable opportunities even during the turbulence periods on the market, which supports covered interest rate parity.

However, not all studies unequivocally support that deviations from CIP condition are not exploitable and economically insignificant. For instance, Akram, Rime and Sarno (2008) show that short-lived violations of CIP arise. Thus, deviation from CIP big enough to be economically significant and their duration is, on average, high enough to allow FOREX market participants to exploit them. However, these opportunities amount to small numbers when one compares them to the total number of observations examined. Akram et al. (2008) employ tick data on three major exchange rates: USD/EUR, USD/GBP and JPY/USD. Average duration of found deviations was from 1 to 4 minutes. Although, duration is high enough for deviations to be exploit with current advanced algorithmic programs, but low enough to explain why such opportunities have gone undetected in much previous research using data at lower frequency. However, one can safely assume that at daily or higher frequencies arbitrage opportunities will not be observed. Overall, study gives the mixed evidence on CIP condition appealing that arbitrage opportunities exist, exploitable and economically significant, but short-lived as market restored to equilibrium.

Research conducted by Baba and Packer (2009) conducted for the purposes of interpreting deviations from covered interest parity during the financial market turmoil of 2007-2008. This period is associated with European banks increased USD activity to secure USD lending to fund US conduits and, simultaneous, US financial institutions became much more cautious about lending USD. Majority of European banks moved to convert EUR into USD via FOREX interbank swaps. European banks deepened into a phenomenon of global dollar shortage. Heightened counterparty risk implied risk premium charged by lenders of USD swaps. This study covers a period that ends in September 2008 shortly before the bankruptcy of Lehman Brothers. Empirical results imply more

persistent deviation from CIP in times than counterparty risk between European and US financial institutions is boosted and deteriorating liquidity in FOREX swap market. Baba and Packer conclude that USD funding actions by ECB and enhanced USD credit lines from Federal Reserve stabilized market by lowering volatility of deviations from CIP. Hence, in high turbulence condition some persistent deviations from CIP take place.

Overall, the empirical evidence suggests that CIP fits the data pretty well. Generally, deviations from CIP cannot be exploited and lie in neutral band, so covered interest arbitrage does not seem to entail unexploited opportunities for profit. However, in data with high frequency occasional exploitable violations of CIP occur after accounting for transaction costs, but they are short-lived. Violations also associated with periods of financial turmoil and exceptional market volatility (when transaction costs rise, and the neutral band widens anyway). Beside data digging and financial crisis papers, majority of studies show that CIP holds on average, accounting for buy-sell spreads.

### 3. UNCOVERED INTEREST PARITY

Unlike CIP, uncovered interest parity (UIP) implies no- arbitrage condition without forward contract hedging against exposure to exchange rate risk. Transactions are conducted only in the current market. The change in spot exchange rate is estimated on its expected value. As such, if markets are efficient, expectations are formed rationally by risk neutral traders, given time  $t$  information,  $\Omega_t$  (formulae 2). Hence, traders are indifferent to interest rate differentials between two countries, thereby uncovered interest riskless profits eliminated by adjustment of exchange rate between those countries.

$$(5) \quad \left( \frac{E(S_{t+k})}{S_t} \right) \left( 1 + i^* \left( \frac{T}{360} \right) \right) = 1 + i \left( \frac{T}{360} \right)$$

UIP asserts that return on the deposit in low interest rate currency (right-hand side of formulae 5) is exactly offset by gain on high interest rate currency deposit and loss associated with high interest currency depreciation (left hand side of formulae 5). UIP is a no-arbitrage condition, so under such equilibrium investors would be indifferent to the interest rate in two countries. Conversely, some shortfall in return on low interest rate currency deposits must be offset by some expected gain from appreciation of the high interest rate currency against the low interest rate currency. For this equilibrium to hold several assumptions should be satisfied, such as: funds flow freely across country borders; investors are risk neutral; assets are substitutable (Copeland 1994).

Vast literature documents that uncovered interest rate parity (UIP) do not hold. On the contrary with the theory, starting with classical studies Bilson (1981) and Fama (1984) empirically show the failure of UIP. Moreover, on average high interest rate currencies tend to appreciate low interest rate currency, so arbitrage opportunities arise. This violation of UIP is often referred as “forward premium puzzle”.

Beside arbitrage benefits, potential failure of UIP embeds essential importance for policy measures. According to Flood and Rose (2001), "deviations from UIP are the basis for interest rate defense of fixed exchange rate". Since interest rate defense of fixed ex-

change rates is similar to the use of interest rate policy to stabilize an exchange rate, failure of UIP also ensures the effectiveness of interest rate policy to stabilize an exchange rate (Flood et al. 2001).

### 3.1. Forward Rate Unbiased Hypothesis

The Unbiased Expectations Hypothesis states that forward rate should be an unbiased predictor of future exchange spot rate at  $T$  when the forward contract matures and also reflects market expectations at time  $t$ . Such as, in formulae  $E$  is the rational expectations operator given an information set  $\Omega_t$ . If it does not hold, investors can earn arbitrarily large profits by speculating in forward foreign exchange markets and the arbitrage theory is violated. The Unbiased Expectations Hypothesis (UEH) is also closely related to the FRUH (Forward Rate Unbiasedness Hypothesis) (Razzak 1999).

UEH Joint Hypothesis assumes that: (i) investors form their expectations rationally (marginal) according to given set of information (ii) investors are risk-neutral (or if risk averse they know the process generating equilibrium expected returns). FRUH implies that under the above assumptions, if the forward market is efficient, the forward rate will be an unbiased predictor of the future spot rate (Razzak 1999).

However, several empirical studies showed that it is not the case in real world (review of those studies in the following chapters). Hence, the following scientific question aroused: How accurate is the forward rate in predicting the actual future exchange spot rate at  $T$ ?

### 3.2. Evidence on Forward Premium Puzzle

Several decades one of the most important puzzles of international finance is the failure of uncovered interest rate parity. The vast literature is dedicated to UIP failure and forward premium puzzle. In risk- neutral world forward exchange rate should consistently

predict future spot rate. Empirical studies have been rejecting this prediction, starting from the classic contributions of Hansen and Hodrick (1980), Bilson (1981) and Fama (1984).

Although first studies managed to capture the violation of UIP anomaly were conducted in early 1980's, but idea of testing UEH appeared earlier. Thus, Cornell (1977) in his paper investigated the issue of foreign exchange market efficiency by conducting autocorrelation function test on nine currencies rates from 1973 to 1975 including Arab oil embargo and recession period. As the result Cornell found no evidence of market inefficiency and concluded that results support UEH (FRUH). Subsequently, Levich (1979) using different estimation techniques, including regression based model (without taking first differences), tested FOREX market for violation of market efficiency. Not accounting for stationarity issue, Levich could not reject null hypothesis and discovered only that the market is volatile and profitable opportunities possible. Overall, Frenkel (1980) concluded that test techniques in previous studies have low power, which leads to statistical inability to reject the null hypothesis. This statistical issues and the ensuing spurious regression problems subsequently suggest testing UEH/FRUH hypothesis using regression model with stationarity issues is flawed. Stationarity assured by converting variables into percentage changes by taking log differences of exchange rates.

One of the first paper rejected the simple efficiency hypothesis was Hansen et al. (1980). Implementing logarithmic framework the assumption that forward rate is market-conditional expectation of future spot rate is tested. Using data sample from first half of 20th century they found that return on speculation in forward foreign exchange market is not zero. Later Bilson (1981) extended previous tests of hypothesis by considering a data set of nine currencies from 1974 to 1980. Statistical test was conducted taking as null hypothesis assumption that exchange rate evolves as random walk, so according to martingale process, best possible predictor of future spot rate is current rate. Hence if market satisfies the condition of efficiency forward rates should be equal spot rates. Bilson found that average return from large number of speculative transactions is significantly differing from zero, which is the evidence of either market inefficiency or



risk premia, transaction and information costs influence on the value of the forward premium.

One of the most important papers providing the breakthrough evidence of forward premium puzzle is Fama (1984) study. By the time of this paper there was general consensus that forward exchange rates have little if any power as forecasts of future spot exchange rates. In this study Fama breaks the forward premium into a risk premium and an expected depreciation premium based on the information set available for investors. By constructing a statistical model on this relation, he finds the relative importance of the risk premium and the expected depreciation premium. The biggest contribution was the establishing of regression framework:

$$(6) \quad \frac{S_T - S_t}{S_t} = \alpha + \beta \left( \frac{F_{t,T} - S_t}{S_t} \right) + \varepsilon$$

Subsequently known as Fama regression, statistical test of given data set gave unexpected result. According to parity condition slope coefficient in (6) should be equal to 1. However, estimation results showed that slope not only not equal 1, but on average much lower than zero. This implies that covariance between risk premium and an expected depreciation premium is negative and large in magnitude than variance of an expected depreciation premium. Hence, results imply that, on the contrary with theory and logic, low interest rate (in Fama case – inflation rate) currencies depreciate (higher purchasing power risk premium) relative to the high interest rate currencies.

Fama's results were confirmed in the later studies. Like, Froot and Thaler (1990) report the average  $\beta$  obtained from 75 empirical studies is -0.88. A few are positive, but not one is equal or greater than the null hypothesis of  $\beta = 1$ . This implies that then home interest rate lower foreign interest rate by one percent home currency tends to depreciate by approximately one percent and vice versa. This is in contrast to one percent appreciation dictated by the unbiasedness hypothesis. Engel (1995) results are consistent with previous studies after running Fama regression on ten major currencies. Engel discovered that two standard error band around the null hypothesis not even close to including

the typical estimate. It was also found that  $R^2$  was very low. That is, the predictive power is almost zero – again a robust finding.

Lewis (2011) illustrates the basic result for monthly returns between August 1978 and October 2010 for the U.S. dollar relative to three representative currencies: the Japanese yen, the Swiss franc, and the British pound. Coefficients are all significant and once again negative, so once again exchange rate is predicted to move in the opposite direction of the forward premium. Hence, conclusion is that puzzle has not gone away over time.

Theory predicts domestic currency will depreciate if forward premium is positive, in real world in fact it appreciates. Thus instead of  $i - i^* > 0$  compensating for future domestic currency depreciation, it indicates an appreciation. Economically those findings are counter-intuitive. For economists, statistical rejection of UIP is uncomfortable as the forward rate systematically predicts in the wrong direction. Not only is this counter-intuitive, it makes explaining the bias very difficult.

Overall, the forward foreign exchange rate appears empirically to be a systematically biased predictor of the actual future spot exchange rate, so profitable arbitrage opportunities arise. Another issue is to explain the observed anomalies. In conjunction with the theory 3 possible explanations take place: (i) inefficiency (or non-rationality); (ii) risk premium (iii) statistical problem due to non-stationarity of  $F$  and  $S$ . This bias is inconsistent with accepted notions of market efficiency and appears difficult to explain using current theories of currency risk premium as explained in Chapter 4.

### 3.3. Trading Strategy: the Carry Trade

Perhaps the most widely used currency speculation strategy is carry trade. To execute carry trade strategy investors sell a borrowed low-yielding currency to finance an investment denominated in high-yielding currency. Beside the method described above,

carry trade could be conducted through future contracts operations. This method involves selling forward currencies which are at forward premium (i.e. forward rate exceeds spot rate) and buying forward currencies which at forward discount. Reflecting uncovered interest rate parity failures by executing carry trade investor can obtain both higher nominal cash flow return and the subsequent exchange rate change also yields a capital gain (Lewis 2011). Hence, carry trade returns can be expressed as:

$$(7) \quad \text{sign } FP_t * (F_t - S_T) / S_t$$

Lewis (2011) by regressing carry trade returns on absolute forward premium showed that betas are significant and mean returns are positive. Despite some reversals carry trade exhibits prolonged periods of gain. However, high standard deviation implies that returns are risky.

Beside the classic theoretical researches there is large body of financial literature approaching carry trade from different angles. Burnside et al. (2006) show that the Sharpe ratio generated by equally weighted portfolio of carry-trade strategies is positive and statistically different from zero. However, with Sharpe ratio of individual currencies around (0.40-0.50) investors most likely would not undertake such position since it is not enough to beat the market (U.S. stocks Sharpe ratio = 0.41). Continuing their research Burnside et al. (2008) found that diversification among currencies boost Sharpe ratio by 50 %.

Burnside, Eichenbaum and Rebelo (2011) show that returns are even better with portfolios of currencies. Historical carry trade returns were conducted from 20 major currencies. Annualised excess returns (Feb 1976-Dec 2010) versus USD were used. Beside carry trade study also test momentum strategy. Momentum strategy assumes buying (selling) forward at beginning of month  $t$  if it was profitable to buy (sell) forward a time  $t-1$ . Burnside et al. (2011) show that in both strategies diversification doubles Sharpe ratio. Sharpe ratio (excess return per unit of risk (standard deviation) equals 0.42 for individual carry trades and 0.89 for portfolio of carry trades. Diversifying across currencies cut volatility from 11.3 to 5.1%. Momentum returns also exhibit diversification

benefits. Furthermore, combining carry trade and momentum in “50-50 portfolio” provide high Sharpe ratio of 0.98 reflecting low correlation between payoffs to the two strategies.

The result of several method to conduct carry and very diverse group of carry traders (from sophisticated hedge funds to housewives), is that there is no official data on carry trade volume. Brunnermeier, Nagel and Pedersen (2009) found that investment currencies are subject to crash risk as the result of possible carry trade unwinding. Carry trade is risk taking activity. For carry traders to get profits, the currency pair either needs to not change in value or appreciate. In Economic downturn when interest rates decrease, investors unwind long positions, when this happens, demand for the currency pair decreases and it begins to sell off. It is not difficult to realize that this strategy fails instantly if the exchange rate devalues by more than the average annual yield. Since carry trades are often leveraged, losses can be even more significant (Brunnermeier et al. 2009).

#### 4. EXPLANATIONS OF CARRY TRADE EXCESS RETURNS

While Hodrick's (1987) conclusion - " We do not yet have a model of expected returns that fits the data" - is equally applicable today, progress has been made. Progress in any scientific field is usually made in small increments. Since 1987 it has been shown that many simple explanations for the forward exchange rate bias do not work. We have ruled many things out, but have not yet settled on the "true" story.

Fama (1984) demonstrates that to explain the findings in the data, the risk premium on holding foreign assets needs to be both: (i) larger variance than the forward premium; (ii) strongly negatively correlated with the forward premium. Existing financial models of risk premium do not typically produce a premium capable of generating the required magnitude of forward bias. Derivations of beta from Fama regression show the idea underlying the forward premium puzzle explanation. Further, beta in (6) is covariance of exchange rate change and forward premium. Assuming efficient markets, expected change in exchange rate equals sum of forward premium, risk premium and error term, beta can be expressed as such:

$$(8) \quad \beta = \left( \frac{\text{cov}(\text{FP}, \text{FP})}{\text{var}(\text{FP})} \right) + \left( \frac{\text{cov}(\text{RP}, \text{FP})}{\text{var}(\text{FP})} \right) + \left( \frac{\text{cov}(\text{ER}, \text{FP})}{\text{var}(\text{FP})} \right)$$

Hence, beta can be expressed in shorter two- term way:

$$(9) \quad \beta = 1 + \beta^{\text{RP}} + \beta^{\text{RE}}$$

Thus, for beta to satisfy null hypothesis must be equal to 1, so empirical results on beta other than one is evidence of either:

- Risk Premium,  $\beta^{\text{RP}} \neq 0$
- Market Inefficiency,  $\beta^{\text{RE}} \neq 0$

In conjunction with the above statement, two broad classes of explanation proposed. Risk premium class of explanation stemmed from the idea that investors are not risk neutral, and the bias in the forward rate's prediction of the spot rate reflects a risk premium. Market Inefficiency/Non Rational Expectations assess forward premium puzzle under condition that investors make mistakes when forming expectations and/or in processing information. Another way to look at the puzzle is market microstructure approach considering limits to speculations.

#### 4.1. Can Risk Factors explain Risk Premium in FOREX market?

Assuming market efficiency leave only second term ( $\beta^{RP}$ ) from (9). Hence, for null hypothesis to hold  $\beta^{RP}$  must be equal to zero. Otherwise, if  $\beta$  general beta would deviate from null condition.

If  $\beta$  appears to be less than zero as, which is consistent with empirical findings,  $\beta^{RP}$  must be higher than one in absolute value. Hence, to explain the data the following two condition should be satisfied:

- the variance of the risk premium needs to be larger in magnitude than the variance of the forward premium ( $\text{Var}(\text{RP}) > \text{Var}(\text{FP})$ )
- strongly negatively correlated with the forward premium

As Lewis (2011) show difficulty arise as the consequence of general equilibrium models of risk premium cannot produce a premium capable of generating this sort of bias. E.g. variance of FOREX versus USD is about 20-50% as variance of U.S. consumption (used as risk factor in C-CAPM) is about 2%.

Risk premium approach assuming regressing excess returns from FOREX currency strategy e.g. a variety of carry trade on vector of candidate risk factors. Academics usually divide risk factors in two groups: (i) Traditional risk factors; (ii) Currency-specific

risk factors. This allows for possibility that markets are segmented. In other words stock and currency traders weight returns on different sets of factors. However, both currency strategies, carry trades and momentum, as well as individual returns should be explained by the same set of factors.

#### 4.1.1. Traditional Risk Factors explanations

Burnside et al. (2011) examined conventional risk factor models using carry trade and momentum monthly returns. Several models were considered, such as:

- CAPM (capital asset pricing model)
- Fama-French 3 factor model
- CAPM + realized stock market volatility
- Various Real Consumption growth rate models

By running the time-series regressions on monthly and quarterly data Burnside et al. (2011) found that among all models only market component of F-F three factor model was statistically significant. However, this coefficient is economically small with the value of 0.045. Moreover  $R^2$  coefficient is positive only for F-F 3FM. Annually Fama-French model estimates the implied annual expected return of the carry trade portfolio should only be 0.3 percent, but actual return of carry trade is 4.6 percent. Although, Fama- French three factor model is good in prediction stock portfolio returns it cannot predict currency portfolio returns.

Villanueva (2007) is not assessing existing conventional risk models, but on the basis of these models and technical analysis trying to construct the predictive model for broad data sample. Villanueva found that moving block bootstrap simulations of null model of UIP plus small sample bias show that simulated trading strategies cannot generate returns as high as actual data.

To conclude, the wide set of conventional factors cannot explain carry trade or momentum strategies. Results of Burnside et al. (2011) suggest observable traditional risk factors explain little of the average returns to carry trade and momentum portfolios. Risk factors have economically large pricing errors. Moreover, simulated with the different techniques strategies do not provide results which are close to actual carry trade returns.

#### 4.1.2. Currency Specific Risk Factors explanations

The difficulty in explaining carry trade returns using traditional risk factor models has led researchers, such as Lustig, Roussanov and Verdelhan (2009) and Menkhoff, Sarno, Schmeling and Schrimpf (2011), to design risk factor models specifically to the average payoffs to portfolios of carry trade strategies.

In similar way as Fama and French (1993) researchers construct portfolio of stocks (based on size and book to market ratio). Lustig and Verdelhan. (2007) and Lustig et al. (2009) formed, respectively, eight and six portfolios of currencies according to their forward discount against the U.S. dollar (other authors usually use five portfolios). Equally weighted portfolio represents excess return from borrowing USD and lending in FOREX. If exchange rates are random walks, then conditional mean of portfolio return would equal average forward discount. Sorting procedure actually generates portfolios with monotonically increasing returns. Sorting portfolios on that basis creates by construction a pattern in betas similar to that in the table, which tend to bias results.

The sorting approach is used by researches to construct risk factors that they then use to price the cross-section of portfolios. Further, researchers developed currency specific risk factors, those factors are as follows:

- Dollar risk factor:  $R_X$  is the average excess return of the 5 portfolios sorted by their currency discount vs USD (Lustig et al. 2007). In Lustig et al. (2009) paper and further researches of other authors this risk factor often referred as DOL.



- $HML_{fx}$  is return differential between S5 (largest discount) to S1 (smallest discount) portfolios. The carry trade strategy goes long S5 portfolios and short S1 portfolios. Factor was introduced in Lustig et al. (2007) paper.
- VOL is a measure of global currency volatility, the average sample standard deviation of daily log FOREX changes vs. USD (VOL is measured monthly). Their volatility factor is constructed on a monthly basis and is the average intramonth realized volatility of the daily log changes in the value of each currency against the USD. Factor was assessed in Menkhoff et. al (2011) paper.
- SKW factor is used to measure coordinated crashing of target currencies. Rafferty (2010) constructs a global currency skewness factor. This factor sorts currencies into two groups, one with positive forward discounts and one with negative forward discounts, subsequently measuring skewness for each group. Similar approach later was used in Burnside et al. (2011) study.

In Lustig et al. (2009) DOL and  $HML_{fx}$  risk factors are appeared to be highly correlated with S1-S5 individual portfolio returns. Betas for average excess return (DOL) factor is statistically significant and almost equals to one. For  $HML_{fx}$  risk factor beta rise monotonically. Coefficient of  $R^2$  is very high for constructed portfolios, caused by sorting portfolios on basis of risk factors, which artificially construct a pattern to betas. Unlike for sorted portfolios,  $R^2$  for equally weighted portfolio much lower, but still statistically significant. However, neither factor has significant beta for momentum portfolio. Although, this model has high  $R^2$  but it is rejected on basis of pricing error tests. Overall, model so cannot explain payoffs.

Menkhoff's VOL risk factor as little impact on DOL. Findings indicate that when global currency volatility increases the returns to holding low (high) interest rate currencies increases (falls). Although, VOL beta negative and significant for equally weighted portfolio but  $R^2$  much lower and neither factor significant for momentum portfolio. Model in general has low  $R^2$  but is just accepted on basis of pricing error tests. Further more momentum issue still holds.

Rafferty's DOL – SKW model show that SKW as a factor has very little impact on the betas with respect to DOL. Findings indicate that during the time when global currency skewness becomes more negative, the returns to holding low interest rate currencies increase and vice versa with the returns to holding high interest rate currencies. That is, low interest rate currencies provide a hedge against currency crashes.

Recent study of Coudert and Mignon (2012) assess 18 emerging currencies show that country default risk influences the excess returns of investing in carry trade investment currencies and lead to higher returns during bullish market, conversely on bearish. Test of Fama regression with country default risk factor (sovereign credit risk default swap spread as a proxy) showed default risk contributes excess returns of carry trade during booms in the economy, yet cannot explain forward bias as the major investment currencies (Australian dollar and New Zealand dollar) have default risk close to zero. Also, model has not been tested with momentum data.

Some studies have different approach to possible explanations of deviations from UIP. Baillie and Chang (2011) prove the carry trade and momentum returns can be incorporated with classic risk factor models. Some dependencies of UIP and arbitrage returns were found. It was found that uncovered interest parity condition is likely to hold in than carry trade strategy exhibit high return and during high exchange rate volatility.

To conclude, conventional factors cannot explain carry trade or momentum strategies. Currency factors may include so explanatory power in explaining carry trade returns, but they fail to explain momentum portfolios. Conversely, currency factors cannot explain the returns to the stock market.

#### 4.2. Market Inefficiency and Forward Premium Puzzle

Another class of explanations focuses on errors in measuring market expectations. Recalling derivations of beta from Fama regression, assuming market inefficiency leave

only  $\beta^{\text{RE}}$  from (9). Market inefficiency group of explanations focuses only on  $\beta^{\text{RE}}$  leaving risk premium apart. Market inefficiency group of explanations of forward bias puzzle attributed to the variety of causes, like:

- Rare Disasters (so-called Peso Problems)
- Time variation in risk tolerance of market participants
- Liquidity constraints and the pattern of Carry Trade returns

#### 4.2.1. The Peso problem and Rare Disasters

One of the most popular example of errors in expectation is the Peso problem. This expectation problem was considered by researchers, like Krasker (1980), Kaminsky (1993), etc., as the way to explain Forward Premium puzzle. During 1960s Mexican Peso notionally pegged to USD, at MEP 12.50 per 1 USD. For many years Mexican interest rates higher than US rates. In conjunction with this, forward discount signaling an expected Peso depreciation, which actually came in 1976. Thus, speculators (ex post) had persistent profitable arbitrage opportunities prior to the actual devaluation. Krasker (1980) inferred forward rate as biased. Potential for “rare” devaluations prominent in currencies with fixed exchange rates. However, flexible rates can follow regimes of alternating appreciation and depreciation.

According to EMH market participants are fully rational and learn instantly, but are uncertain about a future shift in regimes. This leads to incorrect measures of expectations in market data. Hence, there is skewness in the distribution of forecast errors. However, this is simply a measurement anomaly. These rare events can bias  $\beta$  estimate in Fama regressions (Lewis 2011).

Unobservable (which are formed only by expectation) events may occur in future, but do not occur within the data sample, hence unquantifiable. From econometrical point of view these event may be included in the data sample, even though may not occur in the future, which causes measurement bias (Krasker, 1980). According to this assumption

Forward premium puzzle may be a puzzle only due to this measurement error. Burnside et al. (2011) suggest that the same peso event that can explain carry trade returns can also be consistent in explanation of the returns on stock market and currency momentum.

Lewis's (1989) study another perspective on peso problem explaining the forward rate bias. Developing Krasker (1980) idea, Lewis argue that policy change may be unobservable when it occurs, but likely to impact expectations of the exchange rate at  $T$ . Hence, there is a so-called learning effect on the market. Thus, as long as market participants are learning, they are giving a non-zero probability to each probable regime. Whereas, only one regime is actually in force at any time. Further, Lewis finds that learning effect can explain up to 50% of the forward bias to learning issues. Overall, study argues that learning behavior may occur simultaneously with anticipation on future policy change and risk premium.

Summarizing findings, lead to the conclusion of both peso problem and learning models are being small sample problem. They cannot explain the fact that estimates of  $\beta$  are consistently negative. Moreover, the persistence in the forward rate errors for over 25 years is direct evidence against learning by market participants.

#### 4.2.2. Liquidity Risk and Carry Trades

One of the most influential study shedding the light on forward premium puzzle is study by Brunnermeier et al. (2009). Paper examines the processes underlying rare disasters. Rare disasters are often referred as exchange rate movements occasionally happen without fundamental news announcements (e.g. the significant depreciation of the USD against JPY on 7th of October 1998).

Brunnermeier et al. (2009) assumes this movements may be linked to so-called "liquidity spirals". The funding of traders affects and, conversely, is being affected by market liquidity in a thorough way. In the situation when funding liquidity is limited, traders

become more willing to take on positions. This lowers market liquidity, leading to higher volatility. Further, low future market liquidity increases the risk of financing a trade, thus increasing margins (Brunnermeier et al. 2008).

Investment professionals usually view currency speculations as a risky business, they say that refer investment process as: “go up by the stairs and down by the elevator”. Brunnermeier et al. (2009) use data on 8 currencies (JPY, SWF, EUR, CAD, AUD, NZL, GBP, NOK) vs. USD. Calculating realized skewness from daily data within quarterly time periods, study show high interest rate differentials predict negative skewness for carry trade investment currencies. Carry trade are subject to risk. For instance, JPY is a funding currency, with negative interest differential and positive skewness, but NZD and AUD have positive interest differential and negative skewness.

In other words, JPY appeared to have positive Risk Reversal ( $\text{Call} > \text{Put premium}$ ) and NZD and AUD have negative Risk Reversal ( $\text{Call} < \text{Put premium}$ ). Negative risk reversal means market participants attach higher probability to depreciation of underlying FOREX. The bigger the risk reversal in absolute value the bigger this expected FOREX depreciation in magnitude. Negative risk reversal reflects market expectation of negative skewness in distribution of future exchange rates. Investors will require compensation “a risk premium” for providing liquidity and bearing that depreciation risk. So, part of carry trade return can be attributed to the risk premium associated with currency crash risk (Brunnermeier et al. 2009).

Subsequently, Brunnermeier et al. (2009) found some patterns in prediction of future crash risk. Paper discovers that interest rate differentials and past carry returns both strong negative predictors of future skewness. Also, futures positions neg. related to future skewness. Taken together, findings suggest that crash risk is high following periods of high returns with long speculator positions. Hence, possibility that skewness of pay-offs created endogenously by carry trade activity exists.

To measure investors willingness and ability to put capital at risk, consistently with the previous studies, Brunnermeier et al. (2009) implementing CBOE VIX option implied

S&P volatility index. Study show that increase in VIX associated with unwinding carry trades, consistently with the notion that liquidity tends to dry up when VIX spikes. The associated unwinding of carry trades causes negative skewness in carry trade returns.

Consistently with Brunnermeier, study by Clarida, Davis and Pedersen (2009) documents that during high volatility periods (VIX spikes) Fama regression generate beta two to three times greater than unity, hence carry trade produce negative results. While during low volatility periods carry trade earn money, since beta is highly negative (high yielding currencies appreciate).

Liquidity of foreign exchange market received considerable attention in explanations of carry trade excess returns in recent studies. For example study by Christiansen, Rinaldo and Soderlind (2011) test a model of different risk factors combining three different approaches: classic factor models, funding liquidity explanations and limits to arbitrage. By testing returns of DB G10 Harvest index as proxy for carry trade they found that risk exposures of excess returns are highly regime dependent and proved that financial market are strongly co-move during crises. Also it was found that during high volatility periods carry trade excess return are driven both by traditional risk factors (stock and bond returns as proxy) and, even more significantly, by volatility factor itself.

Summarizing the findings, it appears to be the strong link between currency carry and crash risk. Investing in high interest currencies while borrowing in low interest currencies provide negatively skewed returns, causing exposure of carry trades to crash risk. It is still unclear what causes the crash risk on currency markets. There is a possibility that higher volatility leads to lower available speculative capital due to high margins and, subsequently, increased capital requirements (liquidity spiral). Overall, study triggers the problem of necessity of new class macro models in which risk premium influenced by market liquidity and funding liquidity issues (liquidity spirals).

### 4.3. Limits to Speculation and Microstructure perspective

Several research focuses on a microstructure approach to exchange rates. Evans and Lyons (2002) building up the model based on microstructure determinants provide strong empirical evidence that exchange rates are driven by order–flow. Consequently, investigating the trading behavior of market participants who generate order flow may offer deeper insight into the driving factors behind the forward bias.

The limit to speculation hypothesis by Lyons (2001) is based on this idea. It is argued that even though the forward bias is statistically significant it is economically insignificant, in the sense that it is too small to attract speculative capital. First point to support the hypothesis is that if speculative capital is not allocated to exploiting the forward bias, it will persist. Further, institutional investors allocate speculative capital, in large part, on Sharpe ratios. Lyons (2001) further argues that the willingness of traders to take up an investment strategy is limited to strategies with Sharpe ratios above the minimum threshold of 0.5, which turns out to be the annual average Sharpe ratio of the US market over the last 50 years. Furthermore, as a Sharpe ratio of exploiting the bias equals 0.4 is well below most institutions minimum threshold for allocating speculative capital, the bias persists. However, in later studies, for instance, Burnside et al. (2008) show that market participants can exploit forward premium bias with Sharpe ration close to one. Lyons (2001) limit to speculation theory fails to explain these results.

The microstructure bias explanation does not violate market efficiency in the speculative sense of the term, such as no “supernormal” profit opportunities which are unexploited exist. Some researches argue that microstructure approach can be attributed to risk premium class of explanations. Risk aversion is preventing market participants from exploiting the “biased” return differentials as they would do in a frictionless world.

## 5. DATA AND METHODOLOGY

The data used is described in detail in the first part of this chapter. Second part presents the methodological background of the thesis. Time horizon is limited by availability of the data for each currency. Thus, time period for all analyzed exchange rates spans from January 1990 to December 2012, but LIBOR rates occur as they become available. Currency market data and the BBA LIBOR data is received from the Datastream database with the support of the department of Accounting and Finance at the University of Vaasa.

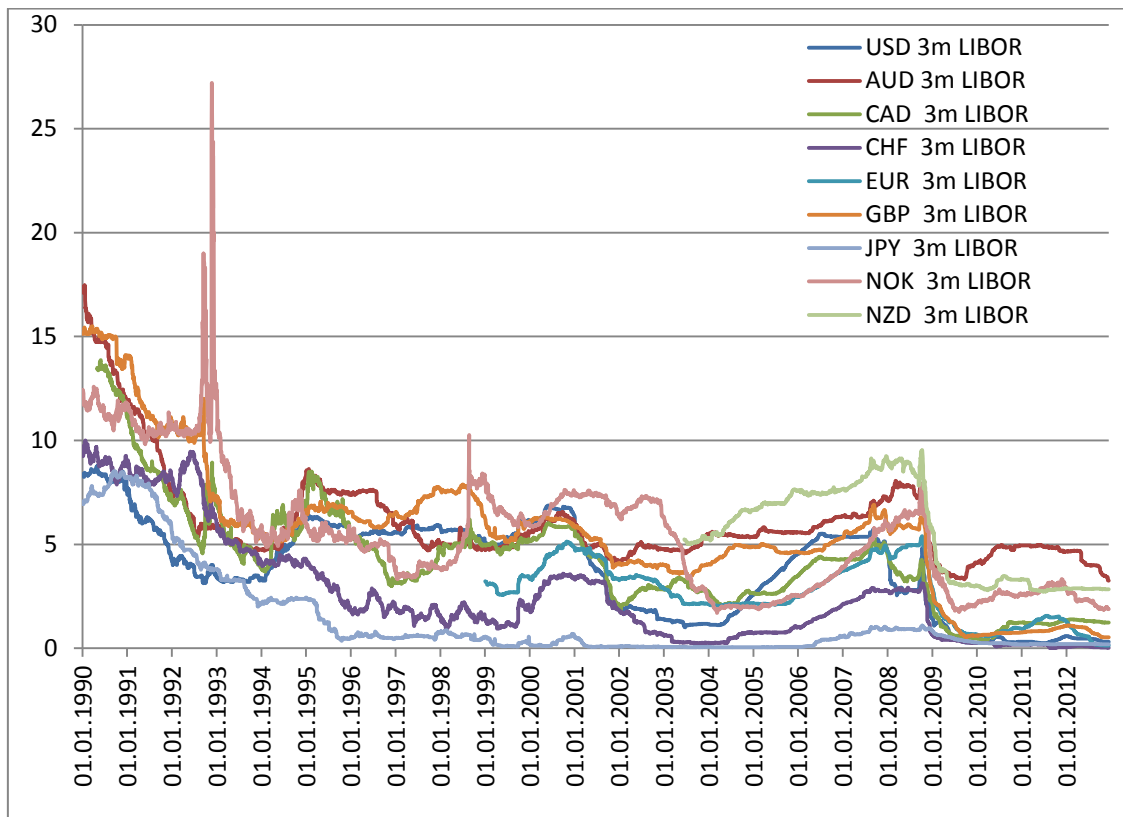
### 5.1. Data Description

For the purposes of further research daily nominal exchange rates to the U.S. dollar (USD) and 3-month BBA London Interbank Offered Rates were collected from Datastream database for eight major currencies. Those currencies are: Australian dollar (AUD), Canadian dollar (CAD), Swiss franc (CHF), Euro (EUR), Great Britain pound (GBP), Japanese yen (JPY), Norwegian krone (NOK) and New Zealand dollar (NZD). All nominal exchange rates data (except Euro) cover the period from January 1, 1990 to December 10, 2012, allowing to capture two recent crises, namely, Asian crisis of 1998 and 2008 global financial crisis. Currency data consist of 5986 daily observations on the five days week basis. For Euro time horizon is limited to the period since the beginning of 1999 to December 10, 2012. Hence, second convention of nominal exchange rate is utilized (units foreign currency per unit of domestic currency (U.S. dollar)). In later tests volatility series of described above exchange rates were computed using generalized autoregressive conditional heteroskedasticity model (GARCH (1,1)). S&P 500 index data used as proxy in the following chapter obtained from Yahoo Finance data source. Time periods are matched.

For the most tests in Chapter 6 quarterly horizon is used to capture nominal exchange rate fluctuations. Hence, 3-month BBA London Interbank Offered Rates appeared to be



appropriate proxy for the interest rates to apply uncovered interest parity straightforwardly. Time period for 3-month LIBOR of Australian dollar (AUD), Swiss franc (CHF), Japanese yen (JPY) and Norwegian krone (NOK) matches time period of nominal exchange rate obtained. But for Canadian dollar (CAD), Euro (EUR) and New Zealand dollar (NZD) period of coverage spans from May 1, 1990, January 4, 1999 and June 16, 2003, respectively. In total 5639, 3448, 2326 observation were collected for CAD LIBOR, EUR LIBOR and NZD LIBOR, respectively. The following figure provide graphical representation of 3-month BBA LIBOR for analyzed currencies:



**Figure 1.** 3-month BBA LIBOR for analyzed currencies over the 1990-2012 period.

London Interbank Offered Rates have been used earlier by Brunnermeier et al. (2009), Burnside et al. (2006), Clarida, Davis and Pedersen (2009), and other researchers to test uncovered interest parity in straightforward fashion. Historically, LIBOR is viewed as fundamental benchmark for global financial markets and calculated daily by Thomson Reuters, to whom major banks provide information about their rates. Daily 3-month LI-

BOR were collected as soon they are published by British Bank Association (BBA). The following section provides perspective on methodological background of the thesis.

## 5.2. Methodology

All of the following tests were conducted in logarithmic framework. Logarithm of nominal exchange rate at time  $t$  is denoted by:

$$(10) \quad S_t = \log(\text{exchange rate})$$

It is assumed in the thesis that to execute carry trade strategy investors sell a borrowed low-yielding currency to finance an investment denominated in high-yielding currency. Reflecting uncovered interest rate parity failures by executing carry trade investor can obtain both higher nominal cash flow return and the subsequent exchange rate change also yields a capital gain (denoted as  $\Delta S_{t+1}$  in the following formula) (Lewis 2011).  $\Delta S_{t+1}$  is basically the indicator of exchange rate excess returns to the prediction of uncovered interest parity. Hence, analogously with other researchers (e.g. Brunnermeier et al. 2009) and denoting foreign interest rate as  $i_t^*$  and domestic as  $i_t$ , carry trade returns are expressed as:

$$(11) \quad Z_{t+1} = (i_t^* - i_t) - \Delta S_{t+1}$$

Mainly, for uncovered interest parity testing interest rate differentials and excess returns of exchange rates expressed to USD are used. However, U.S. dollar is not necessarily a funding currency. For instance, before 2008 crisis investors were exploiting high interest rate differentials between Australia and Japan by borrowing in JPY and opening long positions in JPY. Further, the result of several method to conduct carry and very diverse group of carry traders (from sophisticated hedge funds to Japanese housewives) is that there is no official data on carry trade volume. Hence, the difficulty of stating the

comparative importance of one currency to another arises. Current research utilizes U.S. dollar as a funding currency to provide the comparability of the results.

Burnside, Eichenbaum and Rebelo (2011) show that returns are even better with portfolios of currencies. Historical carry trade returns were conducted from 20 major currencies. Annualised excess returns (Feb 1976-Dec 2010) versus USD were used. Burnside et al. (2011) show that in carry trade strategy diversification doubles Sharpe ratio. Sharpe ratio (excess return per unit of risk (standard deviation) equals 0.42 for individual carry trades and 0.89 for portfolio of carry trades. Diversifying across currencies cut volatility from 11.3 to 5.1%. Since equally weighted portfolio provide higher Sharpe ratio and other gains of diversification, authors conclude that diversification is the key to adjusting portfolio features.

Conducting similar research embed neither scientific nor practical value. Furthermore, simple equally weighted diversification among all analyzed currencies imminently lead to higher transaction cost and difficulties in execution. Thus, this research extends previous literature by applying wavelet methodology to exchange rate dataset. One of the purposes of current research is identifying lag-relationships and time structure of correlations among the most popular carry trade currencies. Previous studies approach the dependencies of the currencies superficially, most studies were limited to descriptive statistics. On the contrary, applied in this research maximum overlap discrete transform method provide possibility to approach interdependence of the currencies in more thorough way. Understanding the dynamic behavior of different currencies of economy embeds relevant practical importance in the implementation of investment strategies (like carry trade) and risk management. Wavelet techniques help to better assess the dynamic behavior of currencies, and even in some degree to predict the direction of movements. Discrete wavelet transform allow analyzing the structure of the data at different scales. Also, the lag relationships that are not visible, while applying a simple cross-correlation analysis, can be analyzed with wavelets.

Each hypothesis is tested applying different methods. Thus, to test first hypothesis logarithmic returns of nominal exchange rates were conducted and used in wavelet correla-

tion analysis, which is mathematically expressed in further paragraphs. To test second hypothesis this study applies the generalized autoregressive conditional heteroskedasticity (GARCH) model to calculate the conditional volatility series. The model used to calculate conditional volatilities is called the constant mean GARCH (1,1) model, where volatility depends on the previous value of volatility and the square of the previous innovation. GARCH series were computed using Eviews 7.0. Mathematical expression is presented in the following formula:

$$(12) \quad y_t = C + \varepsilon_t;$$

$$(13) \quad \sigma_t^2 = A_1 + A_2 \sigma_{t-1}^2 + A_3 \varepsilon_{t-1}^2$$

where  $A_1 > 0$ ,  $A_2 > 0$ ,  $A_3 > 0$  and  $A_2 + A_3 < 1$ , so that the next period forecast of variance is a mix of last period forecast and last period's squared return.

Despite the suitability for finance discipline wavelet methods, the first applications of wavelets in financial disciplines emerged only ten years ago, but they have been applied in engineering for nearly two decades by now. Wavelets have achieved an impressive popularity in natural sciences, especially in earth sciences (e.g. Labat 2005; Grinsted et al. 2004). In the following, the description of wavelet methodology is presented.

Wavelet cross-correlation and cross-covariance methods are based on discrete wavelet transform with maximum overlap (maximal overlap discrete wavelet transform (MODWT)). The mathematical basis of the method considered in Percival and Walden (2000) paper. For this study, the indicator of the wavelet cross-correlation is derived from the model of Percival and Walden and is actually based on the record of the wavelet correlation. MODWT coefficients indicate a change in a certain scale of measurement. Thus, the use MODWT for stochastic time series can provide split data sample on the components of different scales (scale-to-scale decomposition). The basic idea the concept of wavelet variance is to replace the concept of variability for a given scale by global variability measure estimated for the full sample (Percival and Walden 2000). The same applies to the wavelet covariance. Wavelet covariance breaks sample covari-

ance into different time scales. In other words, the wavelet covariance in a certain time frame shows the covariance between two stochastic variables in a given time. Wavelet covariance is expressed mathematically as follows (Gentsay et al., 2001):

$$(14) \quad \text{cov}_{XY}(\lambda_j) \equiv \frac{1}{N} \sum_{t=L_j-1}^{N-1} d_{j,t}^X d_{j,t}^Y$$

where  $d_{j,t}^X$  – MODWT wavelet coefficient of variable X in the scale of  $\lambda_j$  at time t.

This ratio of covariance to some extent inaccurate, because the covariance depends on the changes in the time series. Consequently, there is a need to measure the coefficient of wavelet correlation:

$$(15) \quad p_{XY}(\lambda_j) \equiv \frac{\text{cov}_{XY}(\lambda_j)}{\sqrt{V_X(\lambda_j)V_Y(\lambda_j)}};$$

$$(16) \quad V_i(\lambda_j) \equiv \frac{1}{N} \sum_{t=L_j-1}^{N-1} [d_{j,t}^i]^2$$

where  $V_i(\lambda_j)$  – variance of the stochastic process (Percival 1995).

For an empirical study of the above mathematical expressions MODWT analysis were slightly adjusted. For the purpose of further analysis, it is necessary that the wavelet coefficients are expressed in continuous time. Hence, wavelet coefficient have to have zero mean and be unit root. Analogously with the previous studies (e.g. Torrence and Compo 1995; Graham, Kiviaho and Nikkinen 2012) paper utilizes Morlet wavelet coefficient:

$$(17) \quad \psi(\eta) = \pi^{-\frac{1}{4}} e^{i\omega\eta} e^{-\frac{1}{2}\eta^2}$$

In the Morlet wavelet coefficient,  $\omega$  - dimensionless frequency, similar to previous models, equals to six. Coefficient  $\eta$  is a measure of the continuity of time. According to previous studies, like Grinsted et al. 2004, Ranta 2010 and Graham et al. 2010 the best

wavelet transform is Morlet transform, since it provides perfect balance between time and scale localization. Taking into account the factor of Morlet, a continuous wavelet of  $S$  scale at  $t$  time can be written, as:

$$(18) \quad W^X(S, t) \equiv \frac{1}{\sqrt{S}} \sum_{t=1}^N x(t) \psi^*\left(\frac{T-t}{S}\right)$$

In order to improve the wavelet analysis and identify the related indices movements continuous wavelet transformation was applied, the first for each time series. Then cross-wavelet transform is applied, where  $W^{XY} = W^X W^{Y*}$ . A similar method was used Grinsted et al. (2004) to geophysical data.

To test third hypothesis wavelet coherence methodology, similar to Rua and Nunes (2009) is applied. To measure the coherence of the cross- wavelet transform in the time-frequency space, cross- wavelet coherence analysis is performed. Cross wavelet power reveals areas with high common power. Following Torrence and Webster (1998) as it was done in previous studies (e.g. Grinsted et al. 2004; Graham et al 2012) wavelet coherence of two time series is written with the smoothing operator  $s$ , as:

$$(19) \quad R_t^2(s) = \frac{|s^{-1} W_t^{XY}(s)|^2}{s(s^{-1} |W_t^X(s)|^2) * s(s^{-1} |W_t^Y(s)|^2)}$$

In this method the estimator for interdependencies is now continuous wavelet transform, instead of discrete wavelet transform used in previous methods. Calculations are performed in the software package R - project. This study closely follows the guideline of Grinsted et al. 2004 and, as well, as in Grinsted's study level of statistical significance is determined using Monte-Carlo simulations. The logic of wavelet squared coherency is similar to the one of Fourier analysis. The main difference between wavelet coherence and Fourier analysis is that wavelet coherence spectrum allow to measure to what extent two time series commove not only on each frequency, but also on each moment in time. Applying wavelet methodology it is possible to provide more information about co-movements of two time series.

## 6. EMPIRICAL RESULTS

Co- movements of different stock markets have been studied extensively. However, there is not so many literature about linkages of different currencies. These linkages are crucial to investors, especially carry traders. Information about linkages between currencies give an investor tools for efficient diversification and portfolio management as well as risk management. In this chapter, the time-scale dependent correlation of returns and cross-correlation of conditional volatilities major eight currencies is investigated. Applying wavelet multiresolution techniques provide decomposition on a scale by scale basis and therefore allow to make time scale dependent analysis of major currencies linkages.

### 6.1. Descriptive statistics

Due to the fact that currency market for a long time, in a certain sense, was less transparent than, for instance, equities or bonds, foreign exchange market has only recently become a popular topic of research. With the advent of e-trading platforms various data on trading in the foreign exchange market have become available to broad public. Financial literature well covers major stock and bonds markets, yet there are not so many literature on linkages of currencies. This and following sections of thesis provide the results of the study, embedding significant findings for foreign exchange arbitragers. The information presented below carries significant practical importance, in the sense of building up and unwinding carry trade strategies and currency transactions as whole.

In current section descriptive statistic on selected eight major currencies and carry trade strategies. Data sample includes daily (five-day work week)data on exchange rate and carry trade returns, composed by borrowing USD and investing one of the selected currency on 3-monts BBA LIBOR.

**Table 1.** Descriptive statistics for carry trade returns[illegible]

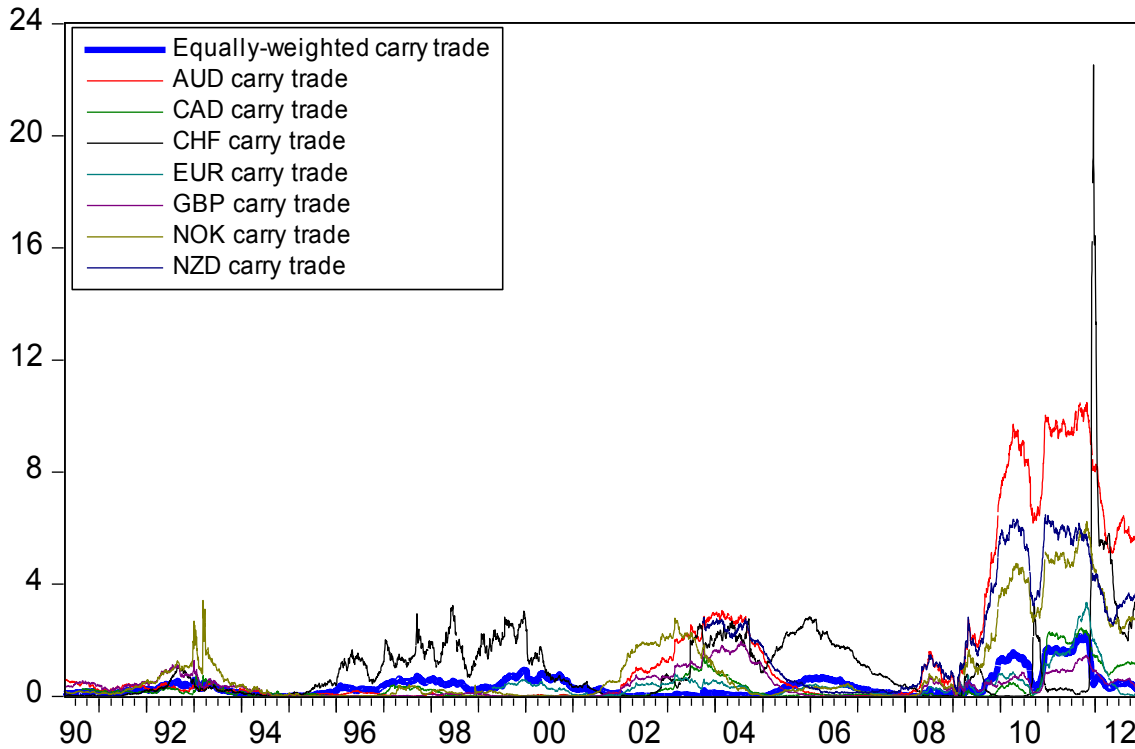


Table 1 reports summary statistics for analyzed most popular carry trade currencies with USD as base currency. Time period spans from January 1, 1990 to December 10, 2012, allowing capturing last two crises (for EUR from January 1 1999 to December 10, 2012). Namely, average currency log-return, average interest rate log-differentials, average excess log returns over UIP with the corresponding standard deviation are shown. Study utilize quarterly horizon of nominal exchange rate change and interest rates for 3 months. In most of the previous paper quarterly horizon was enough to test uncovered interest parity.

Table 1 consist of three parts and provide results for individual currency carry trade strategies for the whole sample, prior Lehman Brothers default on September 15, 2008 and after Lehman Brothers default, respectively. As shown in Panel 1 the individual currency carry trade strategies exhibit returns statistically different from zero, hence, once again, economical and statistical violation of uncovered interest parity is found. Which is the proof that profitable arbitrage is possible on FOREX market. Highest carry trade returns in the last 22 years obtained by investing in, commonly known as investment currencies, New Zealand dollar and Australian dollar. On the contrary Swiss franc and Japanese yen provide negative average logarithmic returns closely associated with negative interest rate differentials. Most of the time those countries had lower interest rate than in the United States. Results are economically significant, since executing New Zealand dollar and Australian dollar carry trade lead to relatively high Sharpe ratio. Perhaps, low returns on Japanese yen carry trade stemmed from the inevitable appreciation of this currency during and prior financial crisis of 2008. This happened as a consequence of rouse demand for yen caused by sudden unwinding of carry trade positions, as Japanese yen is quite popular funding currency.

Defensive actions of regulators after the crises resulted in interest rates raise relative to U.S. dollar's rate, hence investors could exploit higher average logarithmic differentials resulting in higher returns. However, those higher returns, to some extent, can be misleading and result of data adjusting. As shown on figure 2 carry trade returns after 2008 crisis are associated with high levels of conditional volatility in all individual strategies. Thus, taking into account the fact that carry trade is often high leveraged results indicate

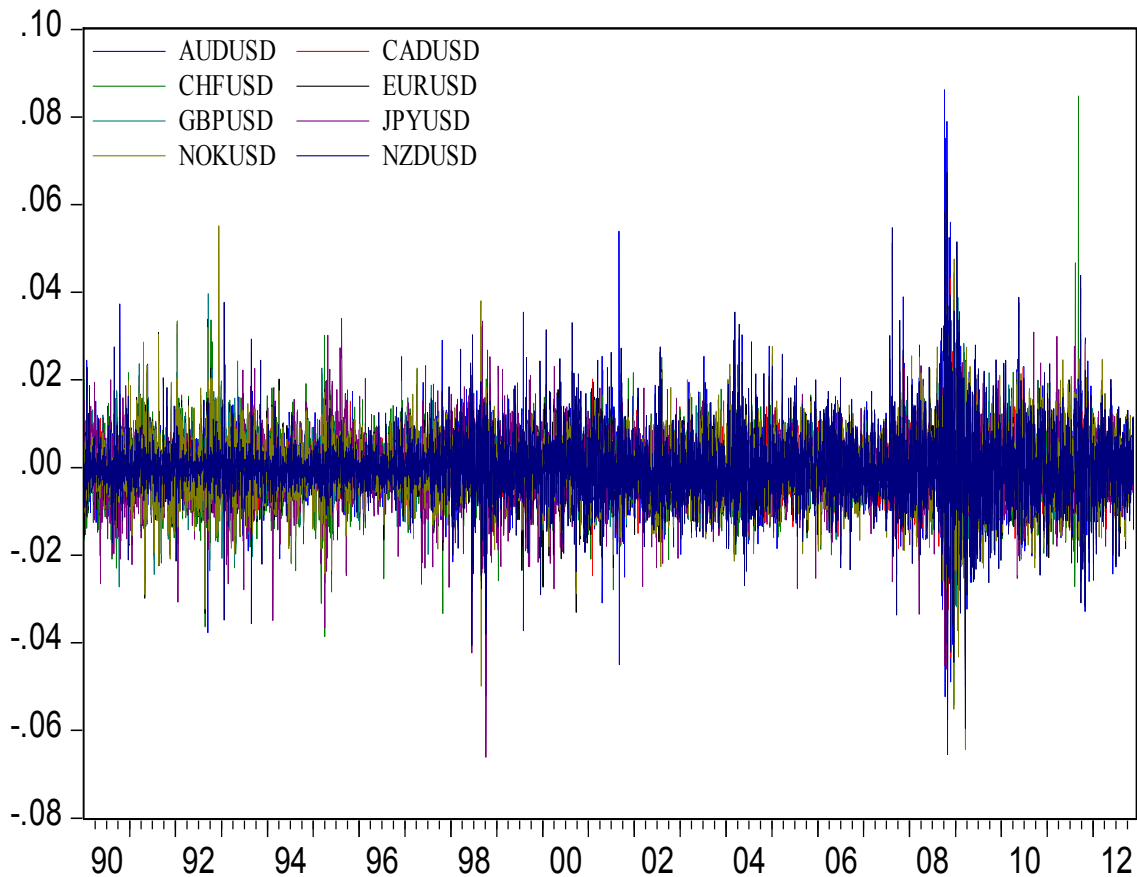
dangers for carry traders associated this fluctuations of currencies. Especially in high volatile environment of today currency market investors need more information about linkages between currencies, which will give tools for efficient diversification and portfolio management as well as risk management.



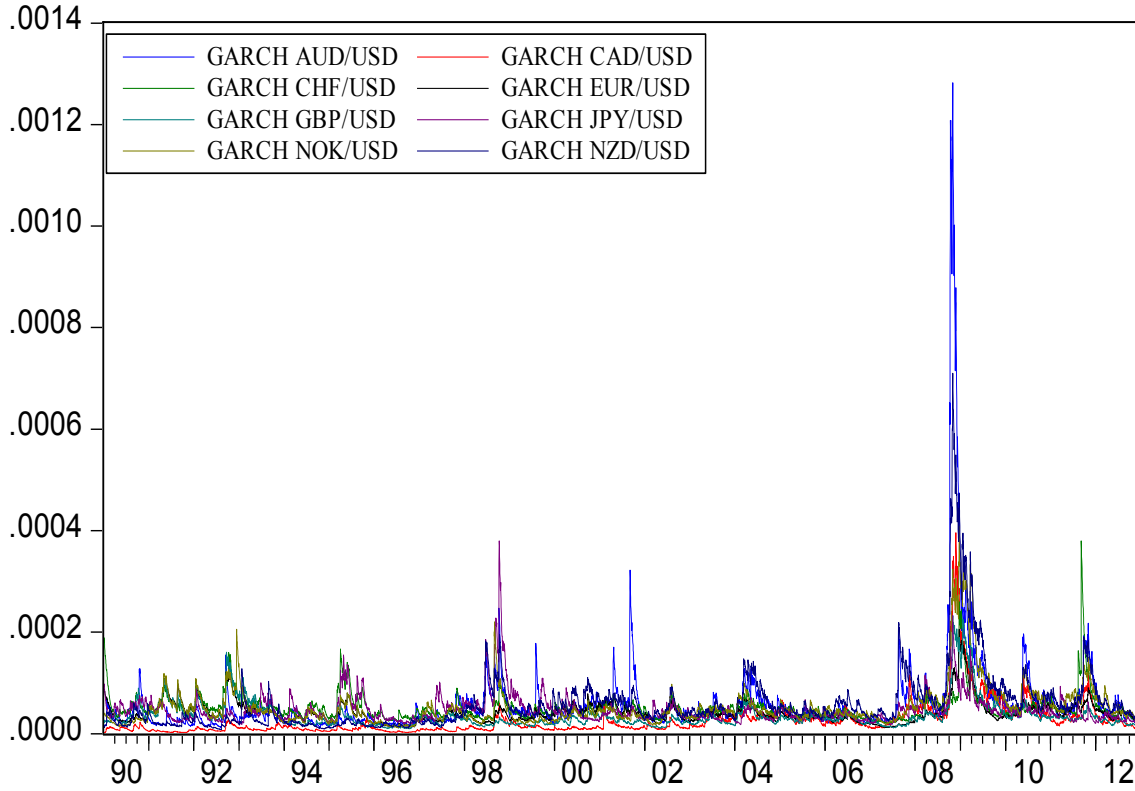
**Figure 2.** Conditional volatility of analyzed currency carry trade strategies. Studied strategies include individual currency carry trade and equally-weighted carry trade. Time period spans from January 1, 1990 to December 10, 2012. Currencies are included to equally-weighted portfolio as necessary for constructing strategy information occurs.

Burnside et al. (2011) show that in carry trade strategy diversification among 20 major currencies doubles Sharpe ratio. Excess return per unit of risk (standard deviation) equals for individual carry trades is twice lower than for portfolio of carry trades. Diversifying across currencies causes cut volatility. Figure 2 provide graphical representation of carry trade's conditional volatility for eight studied currencies, documenting similar results with Burnside et al. 2011. Volatility series were conducted utilizing GARCH (1, 1) model. Equally-weighted carry trade appeared to be less volatile relatively to in-

dividual currency carry trades. Although, eight-currency diversification results in volatility reduction, but does not lead to more attractive economical features of the strategy. Hence, obtained results necessitate the need of further detailed analysis of carry trade components, such as interest rate differentials and nominal exchange rates. Further sections of this study focus on linkages of different currencies. These linkages are crucial to investors, especially carry traders. Information about linkages between currencies give an investor tools for efficient diversification and currency portfolio management as well as risk management. Thereby, information about behavior of exchange rates in time and sudden movements substantial for currency arbitragers of any kind.



**Figure 3.** Logarithmic returns of studied eight currencies. Time period spans from January 1, 1990 to December 10, 2012, for EUR/USD from January 1, 1999 to December 10, 2012.



**Figure 4.** Conditional volatility of studied eight currencies. Time period spans from January 1, 1990 to December 10, 2012, for EUR/USD from January 1, 1999 to December 10, 2012.

Graphs above present descriptive statistics on studied exchange rate returns and volatilities, highlighting the base for later conducted wavelet multiresolution analysis. Figures 3 and 4 show higher fluctuations of returns and higher volatility in the periods of crisis than on bullish market. Dataset utilized in this paper captures Asian crisis and Global financial crisis of 2008. During Asian crisis Japanese yen and Australian yielded most negative returns. Also, these two currencies were associated with higher volatility. Asian crisis, Global financial crisis associated with high return fluctuations of all currencies. Expectedly, behavior of currencies is similar to fluctuations of major stock markets during the financial turmoil. Moreover, relevant for carry traders sudden fluctuation (so called rare disasters) of carry trade can be seen on figure 3. Rare disasters are often referred as exchange rate movements occasionally happen without fundamental news announcements (e.g. the significant depreciation of the USD against JPY on 7th of October 1998). Brunnermeier et al. (2009) assumes this movements may be linked to

so-called “liquidity spirals”. The funding of traders affects and, conversely, is affected by market liquidity in a thorough way. When funding liquidity is shrunk, traders become more willing to take on positions. This lowers market liquidity, leading to higher volatility. Further, low future market liquidity increases the risk of financing a trade, thus increasing margins. Such fluctuations make carry trade with leverage subject to crash risk and evolve negative skewness of excess to UIP return distribution.

Figure 4 depict conditional volatility retrospectively generated with generalized autoregressive conditional heteroskedasticity (GARCH) model. The model used to calculate conditional volatilities is called the constant mean GARCH (1, 1) model, where volatility depends on the previous value of volatility and the square of the previous innovation. GARCH series were computed using Eviews 7.0. Global financial crisis of 2008 caused the biggest spikes of all currency’s volatilities over studied period and Australian dollar appeared to be highest spike of volatility among all currencies. Most probably, these spikes result in high volatility of individual currency carry trade strategies after Lehman Brothers collapse depicted in figure 2.

**Table 2.** Pairwise correlations of studied currencies.

| Currency | AUD  | CAD   | CHF  | EUR  | GBP  | JPY   | NZD  | NOK  |
|----------|------|-------|------|------|------|-------|------|------|
| AUD      | 1    | 0,54  | 0,28 | 0,4  | 0,4  | 0,03  | 0,78 | 0,46 |
| CAD      | 0,54 | 1     | 0,23 | 0,34 | 0,34 | -0,02 | 0,49 | 0,41 |
| CHF      | 0,28 | 0,23  | 1    | 0,87 | 0,6  | 0,42  | 0,33 | 0,72 |
| EUR      | 0,4  | 0,34  | 0,87 | 1    | 0,7  | 0,35  | 0,44 | 0,85 |
| GBP      | 0,4  | 0,34  | 0,6  | 0,7  | 1    | 0,22  | 0,43 | 0,65 |
| JPY      | 0,03 | -0,02 | 0,42 | 0,35 | 0,22 | 1     | 0,09 | 0,26 |
| NZD      | 0,78 | 0,49  | 0,33 | 0,44 | 0,43 | 0,09  | 1    | 0,48 |
| NOK      | 0,46 | 0,41  | 0,72 | 0,85 | 0,65 | 0,26  | 0,48 | 1    |

Notes: All correlations are significant at 5 % level.

Table 2 document the pairwise return correlations for all pairs of studied currencies. The highest correlation coefficient is reported for Euro and Swiss franc. Japanese yen and Canadian dollar appeared to have lowest correlation (around zero), among all pairs of currencies. Further, it is noticeable, that no currency has consistently low correlation coefficient with all others. Correlation coefficients of vary in the range of 0 - 0.87 from

pair to pair. Hence, there is a field for future study of correlations and exploring the ways of diversification opportunities.

Although presented above correlation analysis show statistical significant results, as a basis of portfolio composition it could, however, be biased due to possible variations in time structures of such correlation coefficients. Hence, further analysis of diversification opportunities using more advance methodologies is essential. Previous researches mainly were focused on temporal correlation and sometimes its time variations. The contribution of this study is the addition of new dimension for the analysis of most common carry trade currencies correlations. This research utilizes wavelet multiresolution analysis, which focuses on the changes in scale – dimension, instead of time changes framework. Further sections of the thesis document findings of correlation and cross-correlation decomposing on different time scales.

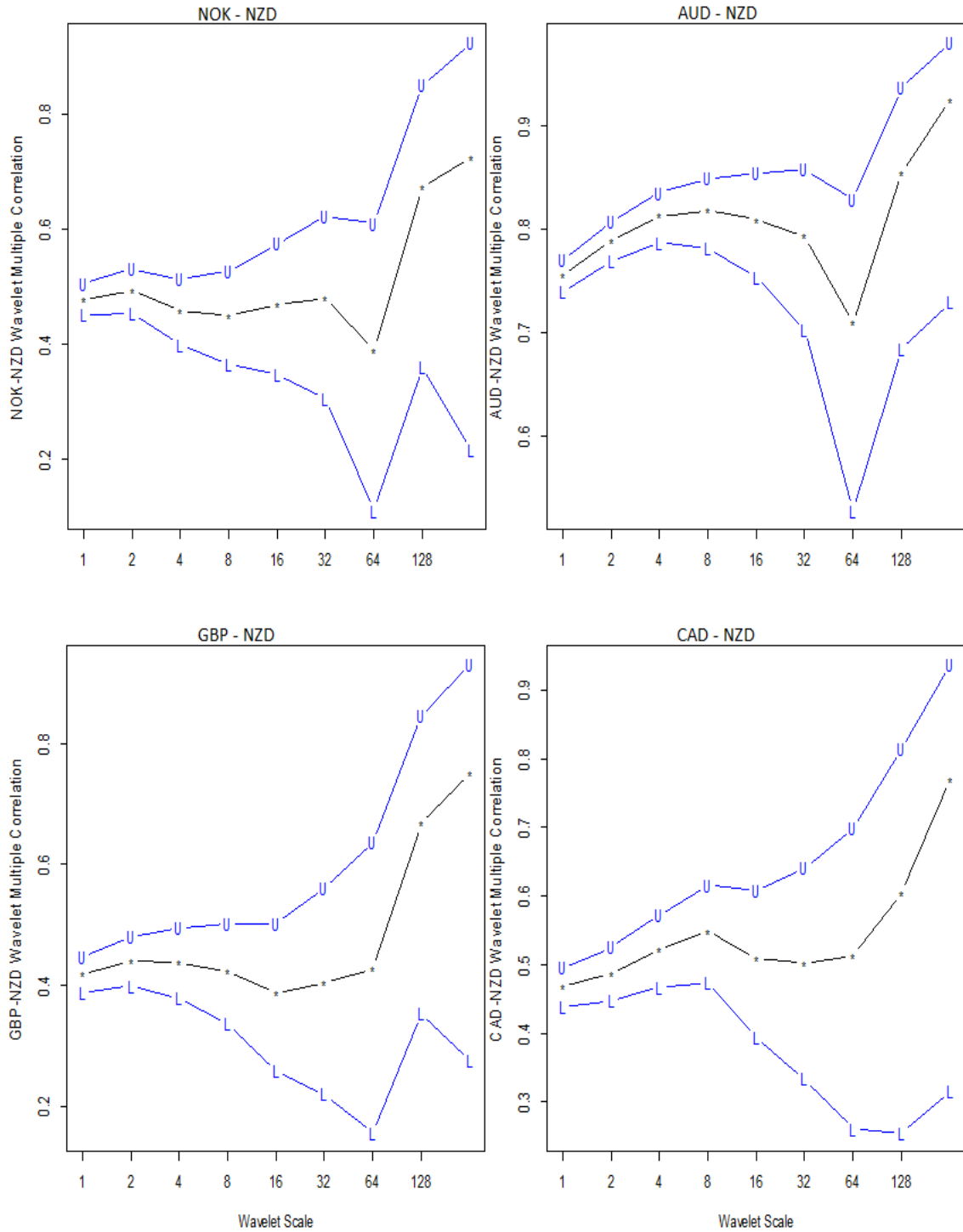
## 6.2. Results of Wavelet Correlation Analysis

Wavelet correlation, as well as wavelet cross-correlation, is a recent method in financial time series analysis. Applying wavelet correlation provide better understanding of the time structure and dynamics of correlations, focusing on the changes in scale-dimension (frequency - dimension). Figure 3 represents wavelet correlations of some studied major carry trade currencies.

Wavelet (MODWT) estimator for wavelet correlation is calculated from daily return series. Wavelet analysis was performed with eight scales decomposition. The first scale represents 1-2 days averages and the scale number eight represents 128-256 days averages. . Time scale spans from one day to approximately one year in dyadic steps. Scales are presented on horizontal axis, correlations on vertical axis. To analyze statistical significance 95% confidence intervals are applied. Peculiarity of maximum overlap discrete wavelet transformations is applying upper and lower boundary filters, which are presented an the following graphs as blue lines with U and L markers, respectively.

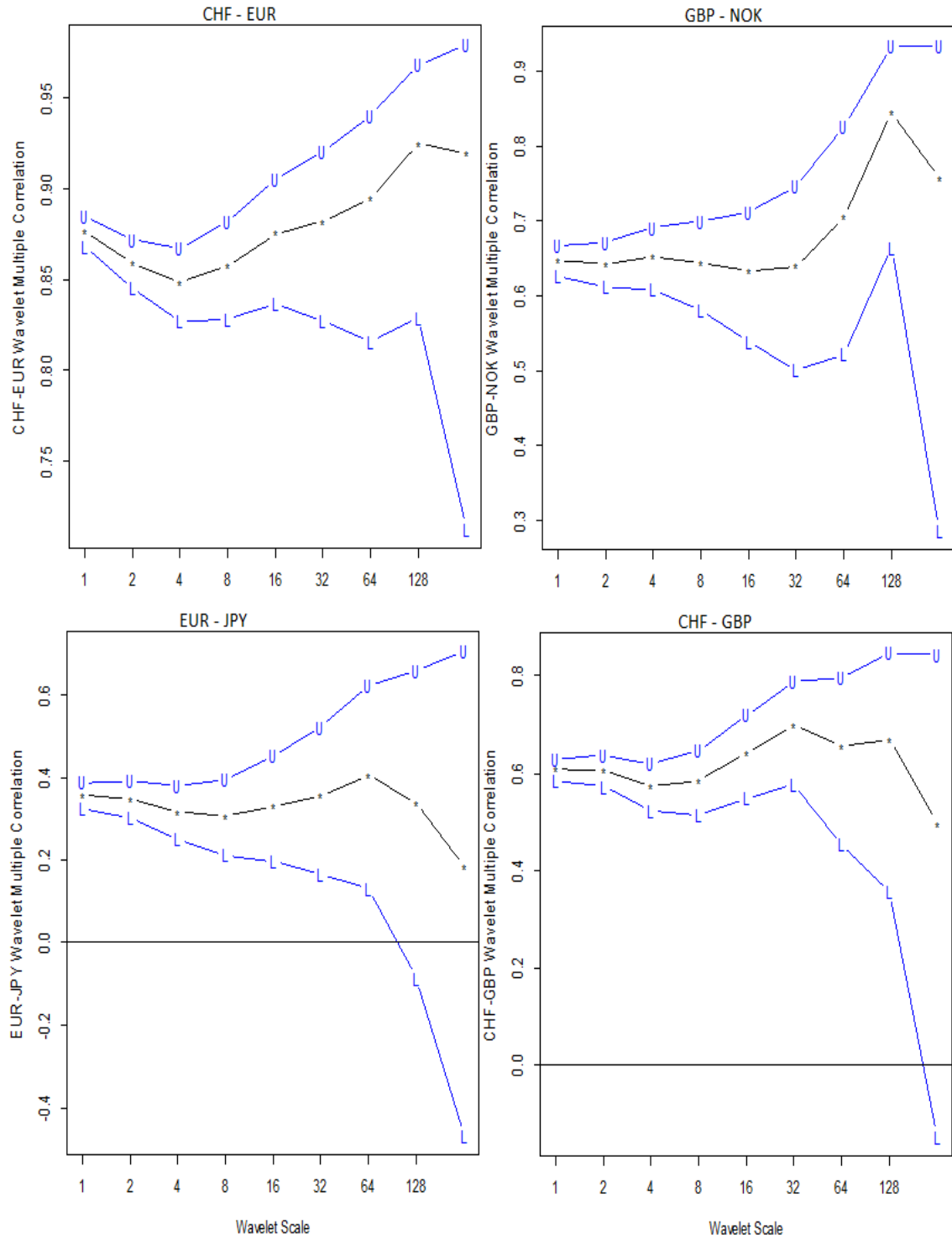
Vast financial literature in some detail reflects the interdependence of major European currencies. However, linkages of other currencies often utilized in the arbitrage strategies have not been studied sufficiently. The novelty of this study is the usage of wavelet correlation, wavelet cross-correlation and spectrum of coherence. These methods allow investors to examine in detail the term structure of correlations at different time scales for different time periods. MODWT transformations allow to break the time series of exchange rate returns into series of wavelet coefficients and, subsequently, to analyze the temporal structure of correlations.

Results of this study confirm the findings of previous research papers on the high degree of interdependence of the European currencies (e.g. Nikkinen et al. 2006; Krylova et al. 2009). European currencies, such as EURO, Swiss franc, the British pound, have relatively high correlation at all levels, which slightly varies with the transition from one time frame to another (e.g. wavelet correlation subfigure of Swiss franc and Euro in figure 6). Although, the most appropriate division of currencies not geographical, but based on the magnitude of interest rate differential against 3-month LIBOR for U.S. dollar. Thus, Norwegian krone and the British pound are rather in the group of currencies with high interest rate differential, in the contrast with Japanese yen and Canadian dollar. Need of the separation occurred not only because of the use of currencies in foreign exchange arbitrage strategies (investment currency and the currency of funding), but also based on the correlation dynamics on different time scales.



**Figure 5.** Wavelet correlation of returns between presented carry trade investment currencies. Corresponding currencies are shown above and on the left side of every subfigure. Time scale spans from one day to approximately one year in dyadic steps.





**Figure 6.** Wavelet correlation of returns between selected currencies. Corresponding currencies are shown above and on the left side of every subfigure. Time scale spans from one day to approximately one year in dyadic steps.

Group of investment currencies (Australian dollar, New Zealand dollar, Norwegian krone and the British pound) are characterized by an increasing correlation than moving to a longer investment horizon. For example, in figure 5 pairwise correlation of selected currencies reach the minimum value at the first level (time scale is from one – two days), whereas the highest value observed in the correlation scale of one year. Therefore, the benefits of diversification among investment carry trade currencies is much higher at short investment horizon, unlike long investment horizon lead to increase in non-systematic risk of currency portfolio. The lowest correlation in this group showed the pair of the British pound and New Zealand dollar on the time scale of one-two days. At the same time, two most popular investment carry trade currencies, namely, Australian dollar and New Zealand dollar exhibit the highest correlation among all pairs. This is probably caused by simultaneous building up and unwinding carry trade positions in those two countries.

**Table 3.** Correlation diversification ranking on five different time scales. Time scales span from a day (scale 1, 1-2 days) to approximately one year (scale 9, 256-512 days). Rankings are built based on efficiency of portfolio diversification.

| RANK  | DAY              | WEEK             | MONTH            | 3 MONTHS         | YEAR             |
|---|------------------|------------------|------------------|------------------|------------------|
| 1   | AUD-GBP<br>0,40* | AUD-GBP<br>0,40* | AUD-GBP<br>0,31* | NOK-NZD<br>0,39* | AUD-NOK<br>0,68* |
| 2   | GBP-NZD<br>0,42* | AUD-NOK<br>0,44* | GBP-NZD<br>0,40* | AUD-GBP<br>0,39* | NOK-NZD<br>0,72* |
| 3   | AUD-NOK<br>0,46* | GBP-NZD<br>0,44* | AUD-NOK<br>0,44* | GBP-NZD<br>0,43* | AUD-GBP<br>0,74* |
| 4   | NOK-NZD<br>0,48* | NOK-NZD<br>0,46* | NOK-NZD<br>0,48* | AUD-NOK<br>0,47* | GBP-NZD<br>0,75* |
| 5   | GBP-NOK<br>0,65* | GBP-NOK<br>0,65* | GBP-NOK<br>0,64* | AUD-NZD<br>0,71* | GBP-NOK<br>0,76* |
| 6   | AUD-NZD<br>0,75* | AUD-NZD<br>0,81* | AUD-NZD<br>0,79* | GBP-NOK<br>0,71* | AUD-NZD<br>0,92* |
| Note: Correlation coefficients are below each named pair. All correlations are significant at 5% level, indicated with *. |                  |                  |                  |                  |                  |

Consequently, all investment carry trade currencies posted low correlation to the funding currencies (Euro, Swiss franc, Japanese yen and, to some extent, Canadian dollar). The only exception is the British pound, which has relatively high correlations to funding currencies (especially European ones) in all scales. Perhaps, this is the result of geographical factor influence. Overall, there is a geographical division between currencies with low interest rate differentials, so the correlation Euro – Swiss franc is the highest among all of the funding currency pairs, whereas, the Japanese yen has a relatively low correlation with European currencies on all time scales. On the contrary with investment currencies, funding currencies do not have unambiguous trend in the term structure of correlations. Table 3 show funding currencies ranked by efficiency of portfolio diversification (based on correlations) on different time scales. Almost in every time scale (except scale 8, three months and scale 9, one year) pair of Australian dollar-Great Britain pound showed lowest correlation among all funding-currency pairs. The correlation of Australian dollar and New Zealand dollar is strong on most of time scales so this pair takes last place in the diversification ranking. However, at least one of the top three for every time horizon consist of one of those and some other currency. If the investment horizon is longer (the time scale of one year) the best results are obtained by using Norwegian krone and most popular carry trade currencies (Australian dollar and New Zealand dollar).

Table 4 reports the mean, standard deviation, and Sharpe ratio associated with the excess returns of four constructed carry trade strategies. Sharpe ratio is positive and statistically different from zero for all strategies and S&P 500 index as a proxy. Equally weighted carry trade portfolio has relatively low Sharpe ratio, this caused by peculiarities of portfolio construction. Portfolio consist of every carry trade (as they occur), even those with negative average logarithmic returns (e.g. Japanese yen, Swiss franc) without switching funding and investment currency. On quarterly basis Sharpe ratio is 0.97 for equally weighted portfolio of carry trade with high differentials and even higher for portfolios constructed based on prior wavelet correlation analysis. In contrast, the quarterly average Sharpe ratio across currency-specific carry trades is 0.42. Clearly, there is a large gain from diversifying carry trade strategy across different currencies. This notion is consistent with previous findings of Burnside et al. 2008.

**Table 4.** Logarithmic excess returns to carry trade strategies (statistics presented on quarterly basis).

| Strategy   | January 1990 - December 2012 |                    |              |
|--|------------------------------|--------------------|--------------|
|  | Mean                         | Standard Deviation | Sharpe Ratio |
| Equally weighted carry trade portfolio   | 0,013<br>(0,008)             | 0,602*<br>(0,006)  | 0,021*       |
| High differentials equally weighted portfolio  | 0,631*<br>(0,009)            | 0,650*<br>(0,006)  | 0,970*       |
| Wavelet correlation based portfolio 1  | 1,058*<br>(0,017)            | 0,839*<br>(0,012)  | 1,261*       |
| Wavelet correlation based portfolio 2  | 0,304*<br>(0,004)            | 0,292*<br>(0,003)  | 1,041*       |
| U.S. stock market (S&P 500 index)  | 0,015*<br>(0,002)            | 0,084*<br>(0,001)  | 0,178*       |
| Notes: Currencies are included in the strategy as all available information occur, like Euro is included in the strategies since the beginning of 1999. Equally weighted portfolio consist of every carry trade (as they occur), even those with negative average logarithmic returns (e.g. Japanese yen, Swiss franc) without switching funding and investment currency. Wavelet correlation based portfolios 1 and 2 consist of individual currency carry trades. Thus, wavelet based portfolio 1 is a combination of New Zealand dollar (all data available since 2003) and Norwegian krone carry trades. Wavelet based portfolio 2 is a combination of Australian dollar and the British pound carry trades. Standard errors in parentheses. Coefficient estimate is statistical significant it is more than two standard errors away from zero, indicated with *. All data is presented on quarterly basis. |                              |                    |              |

Considering the wavelet correlation analysis during carry trade strategy construction boosted Sharpe ratio to 1,261, which highly economically attractive for investors. Applying MODWT transformations allow to break the time series of exchange rate returns into series of wavelet coefficients and, subsequently, to analyze the temporal structure of correlations. This resulted in identification of currency pairs with the lowest correlation coefficient on the time scale of three months (investment horizon used in this research) and, subsequently, construct ranking of diversification efficiency. Strategy building on the basis of diversification efficiency ranking has led to Sharpe ratio 30% higher than the one of portfolio diversified across investment currencies. Even second

best currency pair in the ranking resulted 7.32% boosted Sharpe ratio of wavelet correlation based portfolio 2.

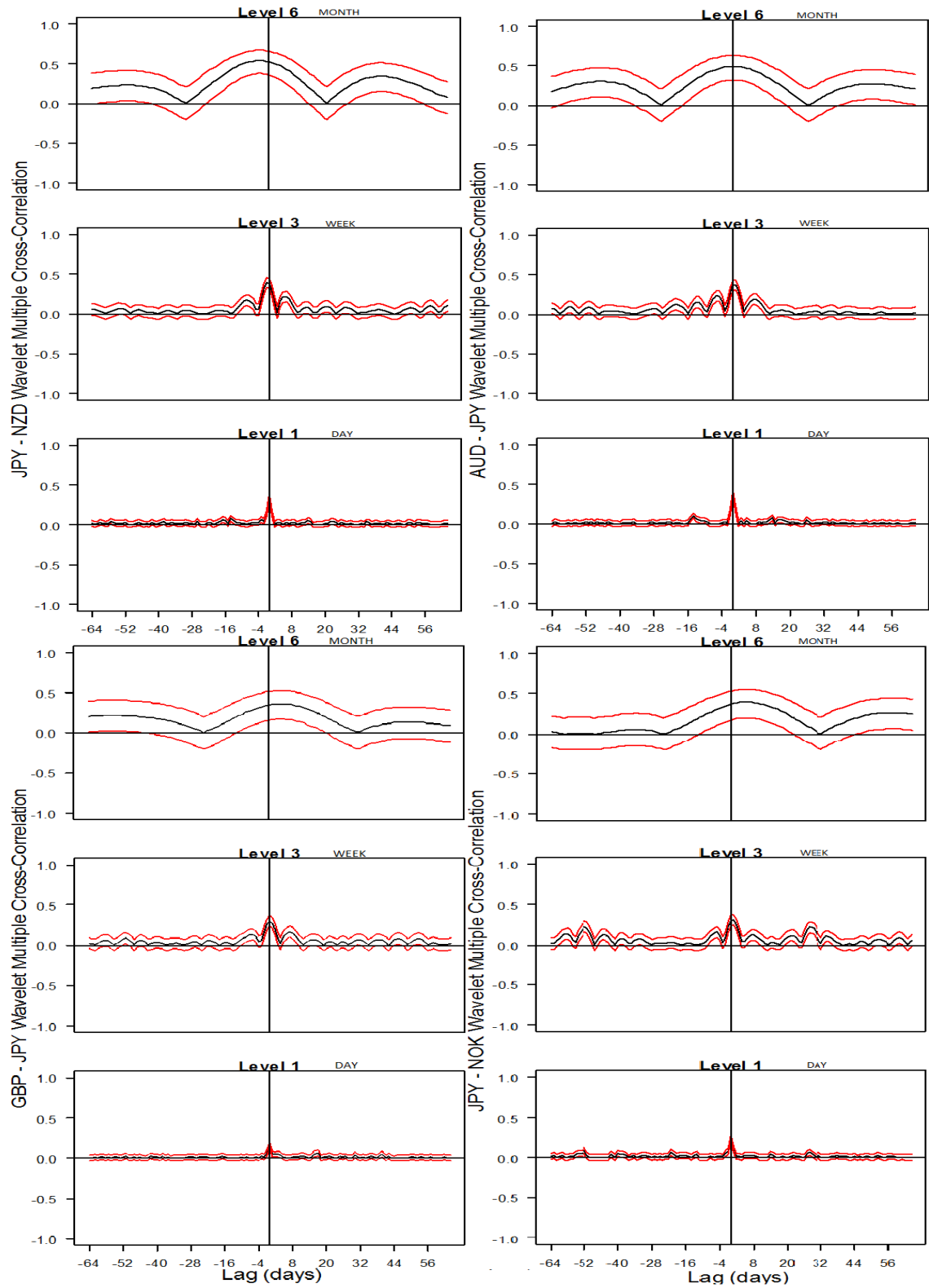
Results documented above support the first hypothesis of the study. Results prove that patterns in exchange rate movements exist and interdependencies with portfolio diversification implications can be found and exploit by investors. Conducted above analysis of term structure of exchange rate correlations and trends in correlations is crucial from the practical point of view, as correlation is the key factor to efficient portfolio diversification, and scientific perspective, as it proves that interrelations between currencies exist and profitable arbitrage is possible. Results are consistent with findings of the previous papers on UIP and, once again prove the existence of statistically and economically significant deviations from uncovered interest parity, hence failure of the parity condition.

To conclude, findings embed significant practical importance for portfolio diversification as the correlations of returns are central factors in efficient portfolio diversification. Understanding of the correlation behavior in time is essential for strategic decision making process; influence the investment horizon choice and relevant for risk management purposes. Strategy building on the basis of wavelet correlations of returns and diversification efficiency ranking has led to Sharpe ratio 30% higher than the simply diversified portfolio. In a group of investment currencies with high interest rate differentials an upward trend in term structure of correlations moving from low to high investment horizons is observed. Despite the presence of such trend, the decision to diversify currency portfolio should be based on the investment strategy and timing of investments. The results of this research help in deciding on diversification of the portfolio of currencies. However, it is not possible to give common recommendations to all investors, because each currency pair should be considered based on time horizon selection, risk aversion and other individual preferences of investors. The whole wavelet correlation analysis data between every currency pair and on every time scale are available upon request from the author.

### 6.3. Results of Wavelet Cross-correlation Analysis of Volatility

Next stage of this study is the scale-based examination of the cross-correlation of volatilities of currencies. The aim is to depict more information about linkages between different carry trade currencies and thus, clarifying the understanding of dynamic structures between them. The MODWT based wavelet cross-correlation functions are used as an estimator. An example of these functions is presented in the following figures with the wavelet cross-correlation functions between carry trade currencies. Wavelet (MODWT) estimator for wavelet cross-correlation is calculated from volatility series, generated with general autoregressive conditional heteroskedasticity model in Eviews 7.0.

Previous studies (e.g. Knif et al. 1995; Ranta 2010, etc.) show the existence of lead-lag relations on a various stock markets. Volatility tend to overflow across borders of different countries causing a chain reaction increasing the fluctuation in asset prices (Knif 1995). Linkages of foreign exchange rate received considerable attention in the last decade papers. Papers by, Krylova et al. (2009), Nikkinen et al. (2006), study linkages of major European currencies volatility implied by foreign exchange options. Krylova et al. (2009) found the leading role of euro among studied currencies. It was found that implied volatility term structure of euro affects all other volatility term structures, while being unaffected itself. Nikkinen et al. (2006) found that market expectations of future exchange rate volatilities are closely linked with leading role of euro agouns the British pound and Swiss franc. Similar study on linkages of foreign exchange was conducted by Matsushita et al. (2007). Again strong linkages between currencies were found, especially during longer time scales. Authors also provide evidence that laeding role of one currency to another is almost vanished during the crisis.



**Figure 7.** Cross-correlations of Japanese yen volatility and volatilities of studied carry trade investment currencies.

Some of the previous studies apply wavelet analysis to foreign exchange rate volatility series. Studies by Ranta (2010), Nekhili et al. (2002), Gensay et al. (2002) indicate the importance of scale-based analysis. Mentioned above studies applying slightly different approaches to different datasets indicate that association between currencies are stronger on lower frequencies and document the leading role of one currency to another. Yet, most of the studies have a limited dataset (e.g. Ranta 2010). Purpose of this paper is to investigate linkages between different volatilities of carry trade currencies and thus, clarifying the understanding of dynamic structures between them.

The results of this section are the proof of the existence of the lead-lag relations in volatility of various currencies and provide information about such relationships. The following diagrams represent the cross- correlation study of exchange rates volatility, supporting the second alternative hypothesis of the thesis. Although, obtained information has a significant practical value for currency arbitrageurs.

Figures 7, 8 and 9 reflect the relationships between different exchange rate volatilities in the scale of one day (scale 1), four to eight days (week scale, scale 3) and month scale (scale 6). Cross-correlations were calculated using the MODWT time series of exchange rate volatilities generated with GARCH (1, 1) model. The purpose of analysis was to test second alternative hypothesis of the research and receive detailed information on links between major carry trade currencies, allowing to some extent predict future exchange rate volatility.

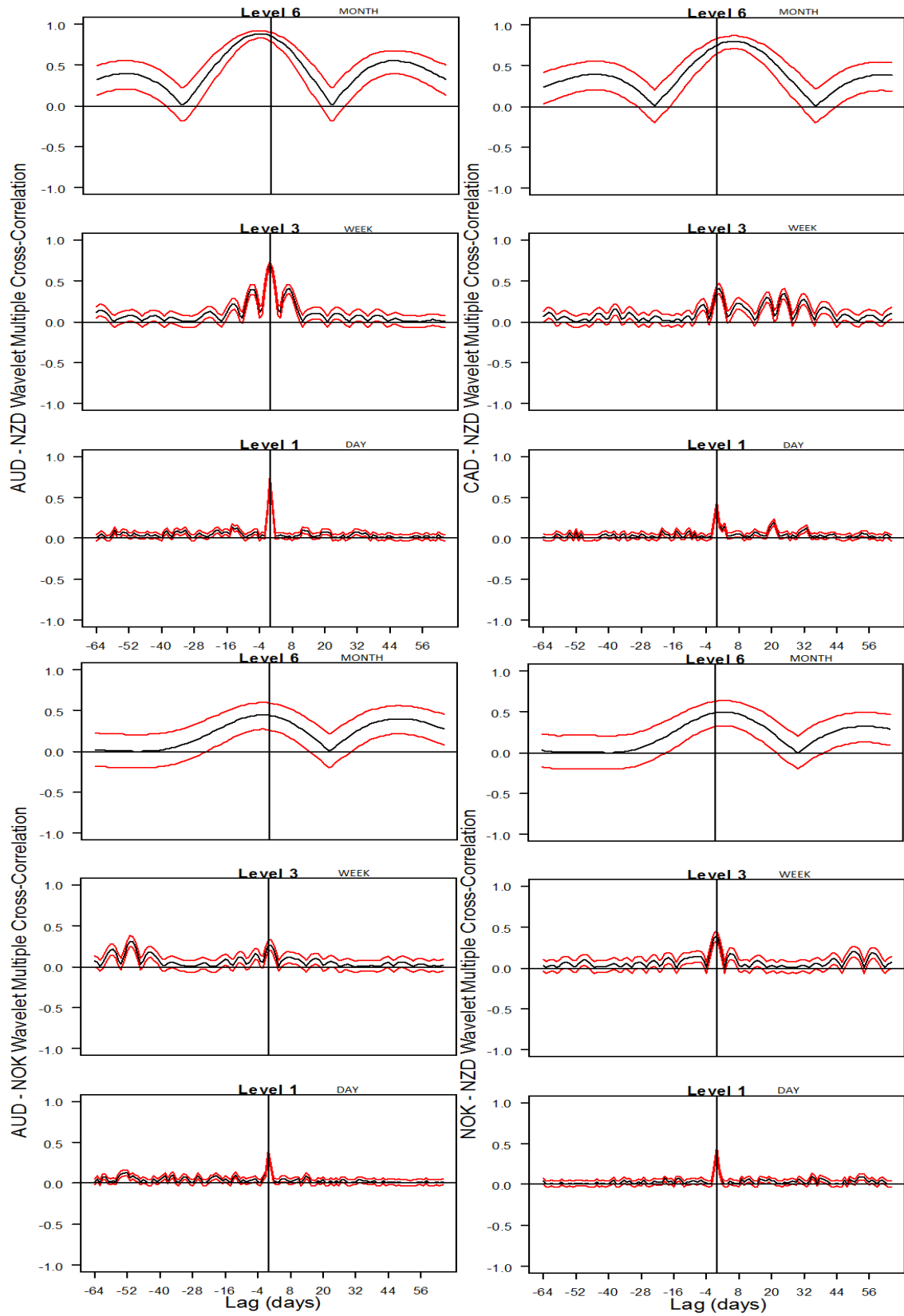
Figure 7 depict the lead-lag relationship of Japanese yen and studied carry trade investment currencies, namely Great Britain pound, New Zealand dollar, Australian dollar and Norwegian krone. The horizontal axis reflects the lag (in days), the vertical – correlation. Analyzed pair is named on the left side of each subfigure. If the cross-correlation distribution is skewed to the left, which means that Japanese yen volatility is leading the volatility of other currencies (for subfigures GBP-JPY and AUD-JPY vice versa). Hence, if volatility of Japanese yen increases (decreases) the volatility of corresponding currency increases (decreases) a few days later.



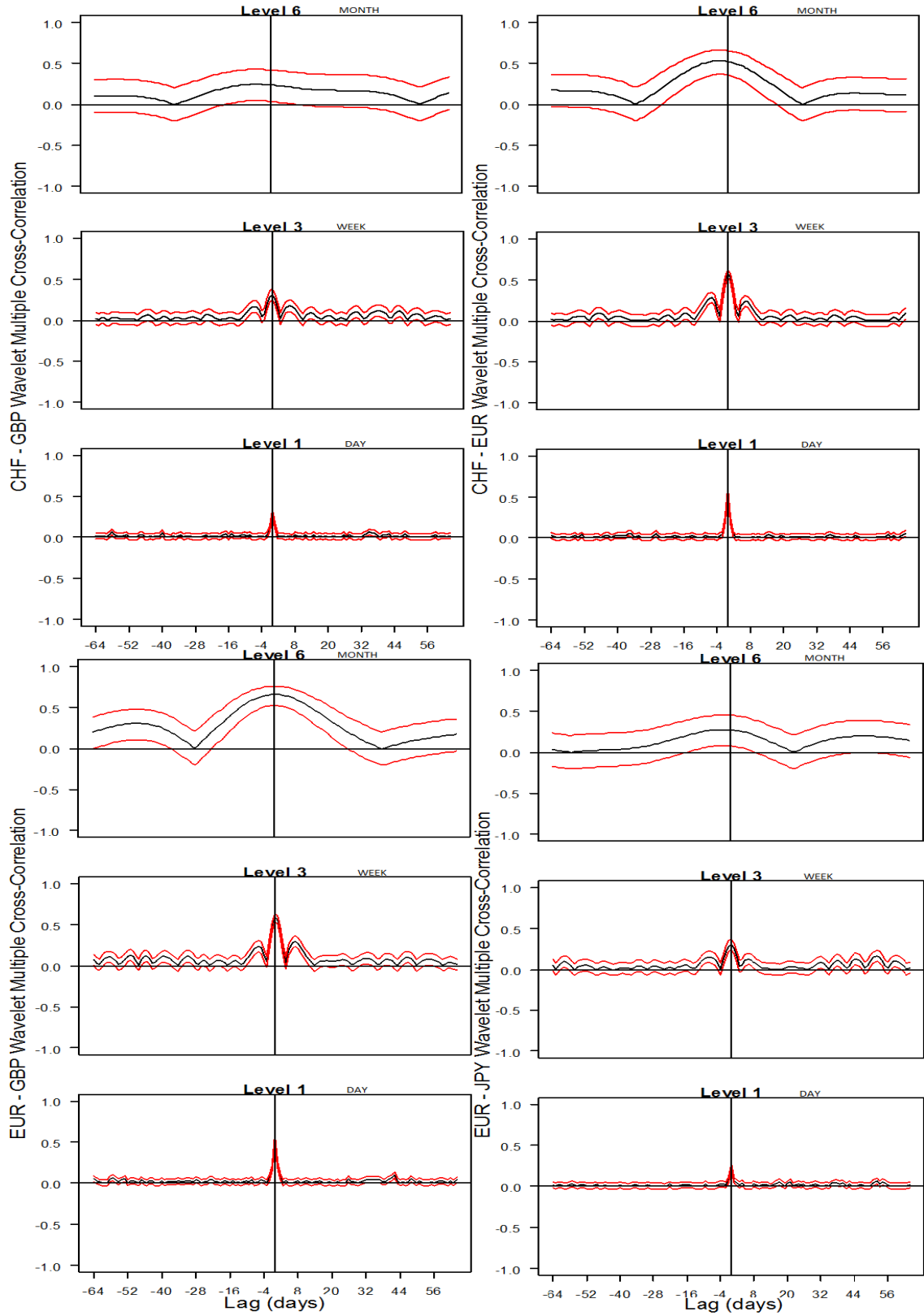
Results indicate the leading role of Japanese yen to investment currencies. The Japanese yen volatility is leading the volatility of Australian dollar, New Zealand dollar and Great Britain pound with the lag of one-two days. Yet, confidently state the same about relations of Japanese yen and Norwegian krone is not possible (the distribution of correlation is relatively symmetric). Perhaps, such clear lead-lag relations of Japanese yen and carry trade investment currencies are caused by the nature of currency arbitrage. Because of the low interest rate Japanese yen is often picked as a funding currency by arbitrageurs, hence changes in volatility of funding currency lead to rapid unwinding (building up) carry trade positions, leading to increase in supply (demand) of investment currency. The consequence of such actions is the increasing volatility in carry trade target-currencies.

These lag-relations are clearly seen in all analyzed time scales (day, week, months). Similarly with previous studies (e.g. Gensay et al. 2002), gradual increase of correlation coefficient is found than moving to longer investment horizon. Again, association between currencies are stronger on lower frequencies. However, described above relations are clearly observed only between Japanese yen and investment currencies, while other potential funding currencies did not post any significant lead-lag relations. Beneficial for the future research could be to study lag relationships with dollar, yet in this study dollar is the base currency.

Obtained results allow investors actively involved in currency trading, in some sense, predict changes of volatility and, therefore, minimize risk. From a scientific point of view, the found lag relations, to some extent is the evidence of foreign currency market inefficiency. The following figures 8 and 9 graphically depict the distribution of cross-correlations of investment and funding carry trade currency volatilities, respectively.



**Figure 8.** Cross-correlation of some investment currencies.



**Figure 9.** Cross-correlation of selected currencies with highest trading volume.

Beside the study of lag relations between yen and investment currencies this paper examines pairwise interdependence of investment and funding currencies separately. Investigation of lead-lag relations between volatility of currencies embeds important information for an optimal carry trade portfolio construction and limitation of non-systematic risk (by predicting possible crash risk). Funding currencies of this study are the most actively traded world currencies (beside U.S. dollar). The study of lag relations of such study is not only practically significant in terms of currency trading, but it is important for all areas of monetary policy and financial decision making.

Figure 8 shows the pairwise correlation of volatility of major investment carry trade currencies. In contrast to lag relations of Japanese yen and these currencies, it is impossible to clearly conclude on the nature of interdependences. For example, in a pair of Australian dollar and New Zealand dollar significant shift in asymmetry is only on a monthly scale, whereas in the time scales of one day or one week distribution of correlations is almost symmetric. This fact suggest either that there is no visible lag relations between currencies, or of simultaneous changes in volatility due to changes in volatility of other countries. Overall, evidence on lead-lag dependences of investment currencies is inconsistent.

If the investigation of interdependence between investment currencies is relatively new field of academic research, the interdependence of actively traded currencies (with low interest rate differentials) is subject of research for a long time. Among many studies, the following findings are complementing with current research. In the early nineties of the twentieth century in Europe was observed the dominance of German mark over other European currencies (Hong 2001). Later research has shown that the fluctuations of “major” currencies exchange rate has significant impact on exchange rate of relatively “small” currencies (Brooks and Hinch 1999).

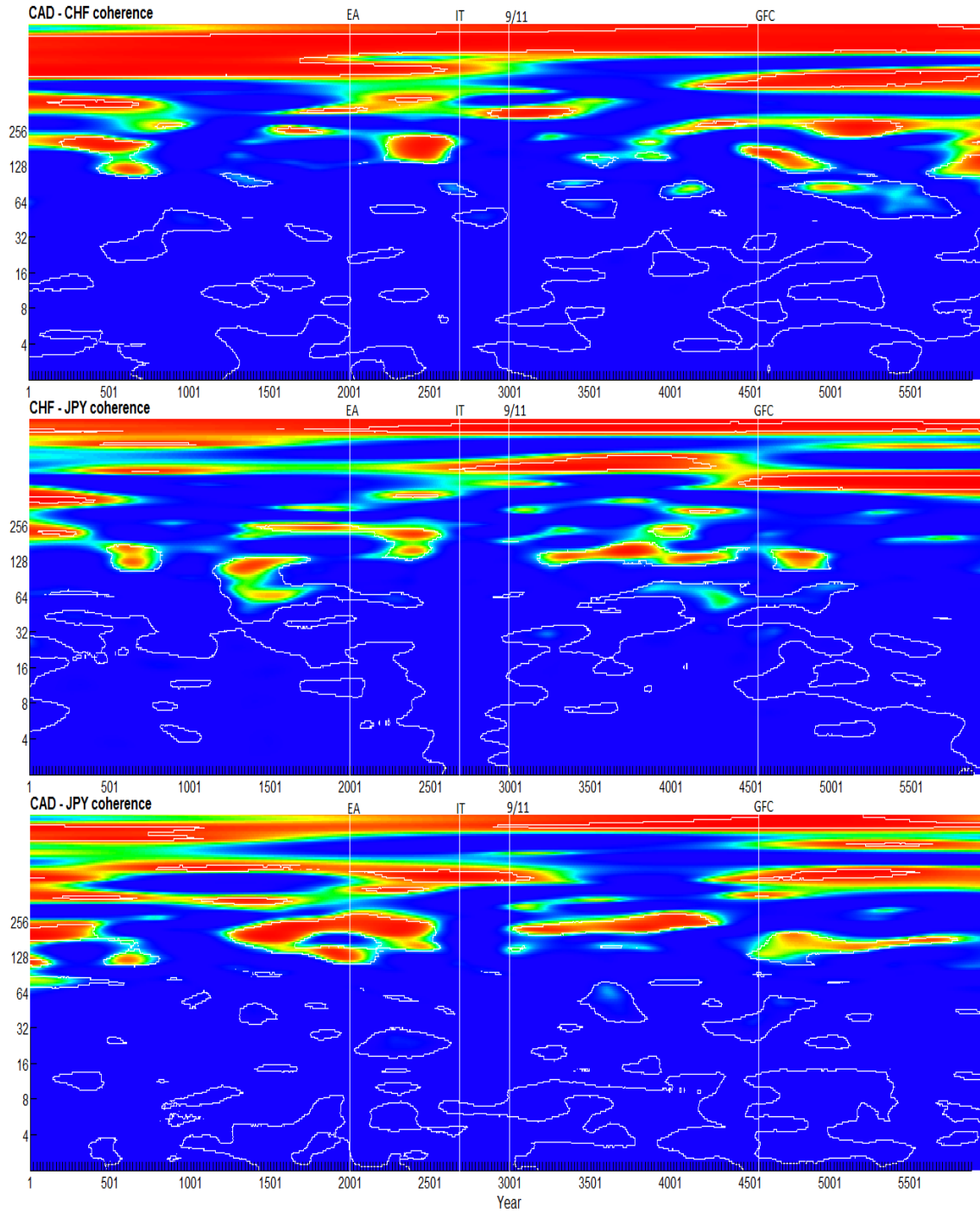
Results of this study presented in figure 9 confirm the findings of previous studies. For example, the cross-correlation function of Euro and Swiss franc volatility suggesting no lead-lag dynamic between two currencies. This trend is observed in all time scales. A pair of the British pound and Euro has almost symmetrical distribution of the cross-

correlation function of volatility. Similar results were found in previous wavelet based studies (e.g. Ranta 2010). Based on conducted above wavelet cross-correlation analysis investors can fairly accurately understand and predict future volatility and direction of exchange rate fluctuations. The whole wavelet correlation analysis data between every currency pair and on every time scale are available upon request from the author.

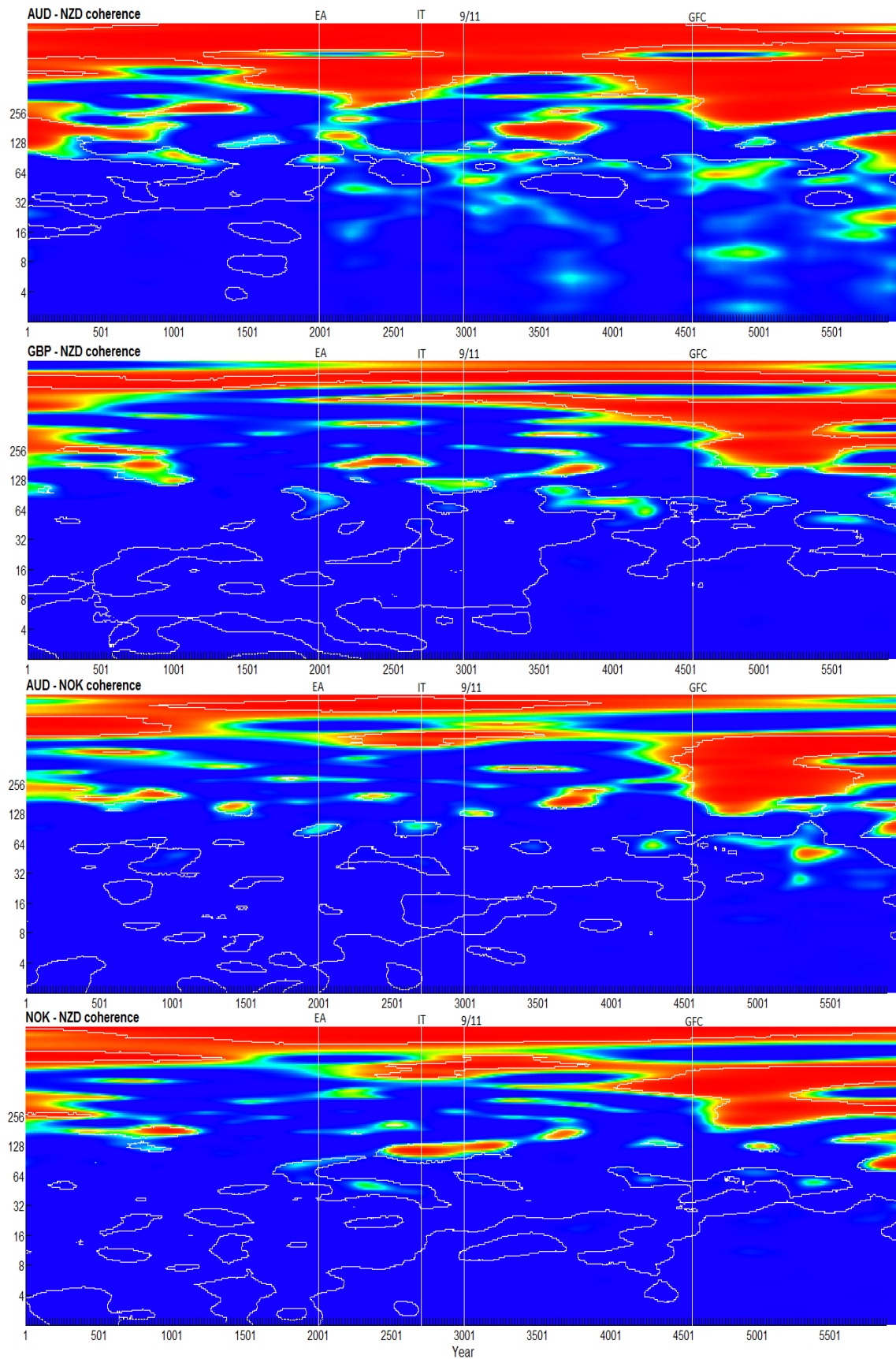
#### 6.4. Results of Wavelet Coherence Mapping

Extensive literature show clear signs of contagion the major stock markets. Previous studies show that short time scale correlation increases during a major crisis, simultaneously long time scale correlations remain approximately at the same level indicating contagion. Contagion phenomenon was studied widely in financial literature. In essence, Forbes and Rigobon (2002) define contagion as an increase of correlation between markets after some crisis. Contagion usually referred as high co-movements of prices during the market turmoil. Also, the overall increase in correlation over time was documented (e.g. Ranta 2010). Contagion, however, mainly was studied on major equity markets. In the following section the previous findings are expanded by analyzing contagion of most widely used carry trade currencies. In order to build graphical representation (figures below) of sectors correlation over time wavelet coherence of the continuous wavelet transform of returns series is applied. This method was extensively covered in recent studies (see e.g., Graham et. al. 2012; Graham et. al. 2011; Grinsted et. al. 2004) to assess interdependencies and co- movements of major stock markets. Thus linkages between major currencies can be studied on different time scales. If the structure along the scale dimension changes in periods of turmoil, it should be an indication of contagion. All of the presented below coherence spectrums were conducted R programming software (codes are in Appendix).

Plotted representation of wavelet coherence spectrum of analyzed funding and investment carry trade currencies is presented on figures 10 and 11 in the following pages.



**Figure 10.** Wavelet coherence spectrum for funding currencies. Time period expressed in numbers of observations from 1 to 5985, respectively from 01.01.1990 to 10.12.2012. Time scales spans from 1 to 512 days for the whole sample period. The information title is seen above every figure.



**Figure 11.** Wavelet coherence spectrum for investment currencies.

**Table 5.** A description of abbreviations used in figures 10 and 11.

| Abbreviation | Event                                      | Date               |
|--------------|--|--------------------|
| EA           | The East Asian Financial Crisis            | July 15, 1997      |
| IT           | The spike of S&P 500 during Dot-COM bubble | March 24, 2000     |
| 9/11         | WTC terrorist attack                       | September 11, 2001 |
| GFC          | The beginning of Global Financial Crisis   | 2007- on going     |

Figures 10 and 11 show integration of funding and investment currencies, respectively, by presenting the wavelet squared coherency spectrum. Wavelet coherency methodology allows analyzing time-and-frequency varying integration of time series, most importantly, within a unified framework. The whole wavelet cross- correlation analysis data between every index and on every time scale are available upon request from the authors. Table 5 provides descriptions to abbreviations and date selected for recent global financial shocks. Those shocks in figures 10 and 11 depicted as white straight vertical line with abbreviation above each line.

The white curved lines isolate the statistical significant part of the map at the 5% significance level. The scale is viewed in terms of the brightness of the red colored areas. Thus, an increasing value of wavelet squared coherence corresponds with a deepening brightness of red. Hence, juicy red area at the bottom (top) of the Figures would indicate strong coherence at high (low) frequencies, whereas a bright area at the left-hand side show strong co-movement at the start (January 1990) of the sample period and vice versa. All the calculations were computed in R programming language. Codes are presented in Appendix 1.

The results of wavelet coherence analysis indicate relatively high dependences of exchange rates at low frequencies (the investment horizon of one year and above). Whereas, at high frequencies high degree of co-movement is observed mainly during financial crises and high volatility on FOREX market. High frequency co-movements during chosen financial shock period clearly seen only among investment currencies (figure 11), while carry trade funding currencies (figure 10) posted less significant results. For



example, pair of Australian dollar and New Zealand dollar clearly exhibits the effect of contagion in the currency market. In this pair there is a significant enhancement of coherency at high frequencies (even on a scale of one day) during the period Global Financial Crisis. Other pairs also exhibit similar phenomena, but the correlation is increased from a time scale of one month (two months for investment currencies). This fact is due to strong link between funding currencies, especially Australian dollar and New Zealand dollar, as they are the main carry trade currencies and speculative activity in these currencies is synchronous.

Despite the fact that previous studies of major stock markets found indication of contagion even at very high frequencies (one-two days), results of these study, to some extent can be viewed as a proof of contagion effect on FOREX market and support for the third alternative hypothesis of the research. Wavelet coherence maps also indicate an overall increase of correlation in most of the cases during the last 22 years, reflecting the facts of integration of world economies, increasing trading volume on foreign exchange market and globalization in general. Thus with gradually increase of correlation over time and, perhaps, strongest contagion effect during on going Global Financial Crisis, in most cases currencies are strongly correlated at the moment. From investor perspective results of wavelet coherence spectrums show that the long-term investment horizon in foreign exchange market lead to lower gains from diversification than short one. The whole wavelet coherence analysis data and spectrum power maps on every time scale are available upon request from the author.

## 7. CONCLUDING REMARKS

Globalization is changing the nature of foreign relations and continuously influencing mechanisms of the foreign exchange market. In response to the deepening of liberalization of world trade and the increasing trend of deregulation of financial markets, globalization makes the "open economy" countries deeply integrated, re-evaluating the possibility of using the foreign exchange market to international currency speculation and currency regulation.

The volume of transactions in the global currency market reaches some days four trillion U.S. dollars. In annual terms, the global currency market trading volume is 12 times more than all the world's stock markets (about 320 billion U.S. dollars a day, according to World Federation of Exchanges, 2009) and 15 times the world's GDP - about 58 trillion U.S. dollars (World Bank 2009). Indeed, only 10% of the volume is associated with maintenance of international trade [13, p.24]. Given the large number of foreign exchange, market and trading volumes, it can be concluded that the market is the most liquid. If any market is efficient it should be the FOREX market. However, there is evidence of systematic ability to earn excess returns over parity conditions in FOREX markets. The most popular strategy for speculative currency trading is - the carry trade. In order to execute the carry trade investors sell borrowed currency with a low interest rate and buy investment instruments denominated in currencies with high interest rates. The theory predicts that the national currency will depreciate if the forward premium is positive, in the real world - it is strengthened. Thus, if the domestic interest rate is higher than the foreign, in practice, the currency will be strengthened over time. Economically, these findings are counter intuitive and illogical. Investing in currencies of countries with higher rates, borrowing in currencies of countries with low rates of income provide a negative skewness, causing carry trade exposure to risk. It is still unclear what causes falls in the currency market. There is a theory that high volatility leads to a reduction of available risk capital due to high margins and, consequently, increased capital requirements (liquidity spirals). Previous studies proved that diversification across currencies lead to carry trade risk reduction. Thus one of the aims of this study is devel-

opment of tools for efficient diversification is essential for portfolio management as well as risk management.

This thesis provides the new perspective for currency portfolio management by studying the linkages of major eight currencies with an implication to the currency arbitrage strategies. The conclusions are drawn from the analysis of the exchange rate with the methods of wavelet correlation, cross-correlation of volatilities and coherence map of exchange rates construction, which is along with chosen dataset, is the main contributions of the thesis. These approaches the analysis of financial time series is quite new. Application of wavelet correlation allows more accurate assessment of the temporal structure and the dynamics of the correlation between the assets.

Results of the wavelet correlation analysis prove that patterns in exchange rate movements exist and interdependencies with portfolio diversification implications can be found and exploit by investors. Conducted above analysis of term structure of exchange rate correlations and trends in correlations is crucial from the practical point of view, as correlation is the key factor to efficient portfolio diversification, and scientific perspective, as it proves that interrelations between currencies exist and profitable arbitrage is possible. In the group of investment currencies with high interest differential upward trend in term structure of correlations is observed. Therefore, the benefits of diversification among investment currency carry trade are much higher at short investment horizons, whereas, the long investment leads to increased non-systematic risk of carry trades. Despite the presence of such trend, the decision to diversify currency portfolio should be based on the investment strategy and timing of investments. Strategy building on the basis of wavelet correlations of returns and diversification efficiency ranking has led to Sharpe ratio 30% higher than the simply diversified portfolio.

Results of wavelet cross-correlation analysis of volatility series allow investors actively involved in currency trading, in some sense, predict changes of volatility and, therefore, minimize risk. From a scientific point of view, the found lag relations, to some extent is the evidence of foreign currency market inefficiency. The Japanese yen volatility is leading the volatility of Australian dollar, New Zealand dollar. Perhaps, such clear lead-

lag relations of Japanese yen and carry trade investment currencies are caused by the nature of currency arbitrage. Because of the low interest rate Japanese yen is often picked as a funding currency by arbitrageurs, hence changes in volatility of funding currency lead to rapid unwinding (building up) carry trade positions, leading to increase in supply (demand) of investment currency.

The results of wavelet coherence analysis indicate relatively high dependences of exchange rates at low frequencies (the investment horizon of one year and above). Whereas, at high frequencies high degree of co-movement is observed mainly during financial crises and high volatility on the market. These results are consistent with the notion of “contagion” by Forbes et al. (2002). The effect of contagion appeared to stronger among currencies with high interest differentials, while, commonly known funding currencies provide inconsistent results. Financial crisis of 2008 appeared to have strongest impact in terms of increased short term correlations at high frequencies, those effects can be observed today. Wavelet coherence maps also indicate an overall increase of correlation in most of the cases during the last 22 years, reflecting the facts of integration of world economies, increasing trading volume on foreign exchange market and globalization in general.

This study can be extended in two following ways. Firstly, beneficial for the future research could be to study lag relationships with dollar, yet in this study U.S. dollar is the base currency. Secondly, as results are consistent with findings of the previous papers on UIP and, once again prove the existence of statistically and economically significant deviations from uncovered interest parity, hence failure of the parity condition, study triggers the problem of necessity of new class macro models to explain obtained excess returns, for example by market liquidity and funding liquidity.

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## APPENDIX: R- CODE ROUTINES

Routine for Wavelet correlation:

```
tui <- read.csv("C:/R/data3.csv", header=T, dec=".", sep=";")
indtimeseries <- ts(tui)
wf <- "d4"
J <- 7
aud.modwt <- modwt(indtimeseries[,2], wf, J)
aud.modwt.bw <- brick.wall(aud.modwt, wf)
cad.modwt <- modwt(indtimeseries[,3], wf, J)
cad.modwt.bw <- brick.wall(cad.modwt, wf)
xx <- list(aud.modwt.bw, cad.modwt.bw)
Lst <- wave.multiple.correlation(xx, N = length(xx[[1]]))
returns.modwt.cor <- Lst$xy.mulcor[1:J,]
YmaxR <- Lst$YmaxR
ind.names <- c("AUD", "CAD")
par(mfrow=c(1,1), las=0, mar=c(5,4,4,2)+.1)
matplot(2^(0:(J-1)), returns.modwt.cor[-(J+1),], type="b", log="x", pch="*LU",
xaxt="n", lty=1, col=c(1,4,4), xlab="Wavelet Scale", ylab="AUD-CAD Wavelet Multi-
ple Correlation")
axis(side=1, at=2^(0:7))
abline(h=0)
```

Routine for Wavelet cross-correlation:

```
tui <- read.csv("C:/R/data4.csv", header=T, dec=".", sep=";")
indtimeseries <- ts(tui)
wf <- "d4"
J <- 6
lmax <- 64
n <- dim(indtimeseries)[1]
```

```

aud.modwt <- modwt(indtimeseries[,2], wf, J)
aud.modwt.bw <- brick.wall(aud.modwt, wf)
cad.modwt <- modwt(indtimeseries[,3], wf, J)
cad.modwt.bw <- brick.wall(cad.modwt, wf)
xx <- list(aud.modwt.bw, cad.modwt.bw)
Lst <- wave.multiple.cross.correlation(xx, lmax)
returns.cross.cor <- as.matrix(Lst$xy.mulcor[1:J,])
YmaxR <- Lst$YmaxR
ind.names <- c("AUD", "CAD")
rownames(returns.cross.cor)<-rownames(returns.cross.cor,
do.NULL = FALSE, prefix = "Level ")
lags <- length(-lmax:lmax)
lower.ci <- tanh(atanh(returns.cross.cor) - qnorm(0.975) / sqrt(matrix(trunc(n/2^(1:J)),
nrow=J, ncol=lags)- 3))
upper.ci <- tanh(atanh(returns.cross.cor) + qnorm(0.975) / sqrt(matrix(trunc(n/2^(1:J)),
nrow=J, ncol=lags)- 3))
par(mfrow=c(3,2), las=1, pty="m", mar=c(2,3,1,0)+.1, oma=c(1.2,1.2,0,0))
for(i in J:1) {
matplot((1:(2*lmax+1)),returns.cross.cor[i,], type="l", lty=1, ylim=c(-1,1),
xaxt="n", xlab="", ylab="", main=rownames(returns.cross.cor)[[i]][1])
if(i<3) {axis(side=1, at=seq(1, 2*lmax+1, by=12),labels=seq(-lmax, lmax, by=12))}
lines(lower.ci[i,], lty=1, col=2)
lines(upper.ci[i,], lty=1, col=2)
abline(h=0,v=lmax+1)
text(1,1, labels=ind.names[YmaxR[i]], adj=0.25, cex=.8)}
par(las=0)
mtext("Lag (weeks)", side=1, outer=TRUE, adj=0.5)
Routine for Wavelet Coherence:

tui <- read.csv("C:/R/data7.csv", header=T, dec=".", sep=";")
indtimeseries <- ts(tui)
x <- c(indtimeseries[,2])

```



```

y <- c(indtimeseries[,3])
ns <- 200
WC <- wc(x, y, no.bs = ns, dt= 1, start = 1, plot = FALSE)
f.n = 2
f.h = 25/25.4
m.t = 0.5;
m.b = 1.5
m.1 = 1;
m.2 = 3;
m.3 = 1;
m.4 = 2
W = 120/25.4
H = f.n*(f.h + (m.1+m.3)*4/30)+ (m.t + m.b)*4/30
tick0 = 0.025;
tick1 = tick0*f.h/(.15*W-m.4*4/30)
fig.h = (f.h + (m.1+m.3)*4/30)/H
fig.b = m.b*4/30/H
fig.w = list(); for(i in 1:f.n) fig.w[[i]] = c( 0,.8, fig.b + (f.n-i)*fig.h,fig.b + (f.n+1-i)*fig.h)
fig.p = list(); for(i in 1:f.n) fig.p[[i]] = c(.8,1, fig.b + (f.n-i)*fig.h,fig.b + (f.n+1-i)*fig.h)
x11(W,H,pointsize = 0)
par(fig = fig.w[[1]],mar = c(m.1,m.2,m.3,0), new = TRUE)
wc.image(WC, p = NA)
axis(1,lwd = .25,at = seq(1, 832, 20),label = NA,tck = tick0)
axis(2,lwd = .25,at = seq(1, 5),label = NA,tck = tick0)
mtext(seq(1, 832, 20),side = 1,at = seq(1, 832, 20),cex = 7/8)
mtext(2^seq(2, 8),side = 2,at = seq(2, 8),cex = 7/8,las = 1,line = .1)
mtext("AUD-CAD coherence",side = 3,at = 1,line = 0.1,font = 2,adj = 0)
mtext("Period",side = 2,line = 1.5,font = 1)
mtext("Year",side = 1,line = 1)
par(fig = fig.p[[1]],mar = c(m.1,0,m.3,m.4),new = TRUE)
wc.power(WC)

```

```
axis(1,lwd = .25,at = seq(.7, 1, .1),label = NA)
axis(4,lwd = .25,at = seq(1, 5),label = NA)
mtext(seq(.7, 1, .1),side = 1,at = seq(.7, 1, .1),cex = 7/8)
mtext(2^seq(2, 8),side = 4,at = seq(2, 8),cex = 7/8,las = 1,line = .1)
mtext("Power",side = 1,line = 1)
wc
```